$2.00

Gates®

Energy Products

CYCLON

Battery Application Manual

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Schematic circuit diagrams set forth in this manual are merely exemplary of recommended charging techniques which may be used and are not intended as construction information.

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Performance features

HIGH VALUE.
You get a high watt-hr. per dollar value because the materials used in Gates sealed lead-acid batteries are readily available and low in cost.

LONG SERVICE LIFE.

Cycle Life
200 - 2,000 cycles
Expected Float Life
8 years

PACKAGING FLEXIBILITY.
You get individual cell availability for broad flexibility in packaging, added flexibility because cells can be used in series or in parallel and may be operated, charged or stored in any position. You can select your choice of voltage and current.

EASY RECHARGE.

Cell Charging

Constant Voltage	
(Cyclic)	2.4-2.6V
(Float)	2.3-2.4V
Constant Current	
(Cyclic)(max)	C/3 rate
(Float)(max)	C/500 rate

WIDE TEMPERATURE RANGE FOR OPERATION

Cell Temperature Range

Storage	-65° C to +65° C
Discharge	-65° C to +65° C
Charge	-40° C to +65° C

SEALED CONSTRUCTION.
You get individual cells in a sealed case that prevents acid, water and acid vapor leakage. The rugged metal case also maximizes resistance to shock and vibration.

LONG SHELF LIFE.

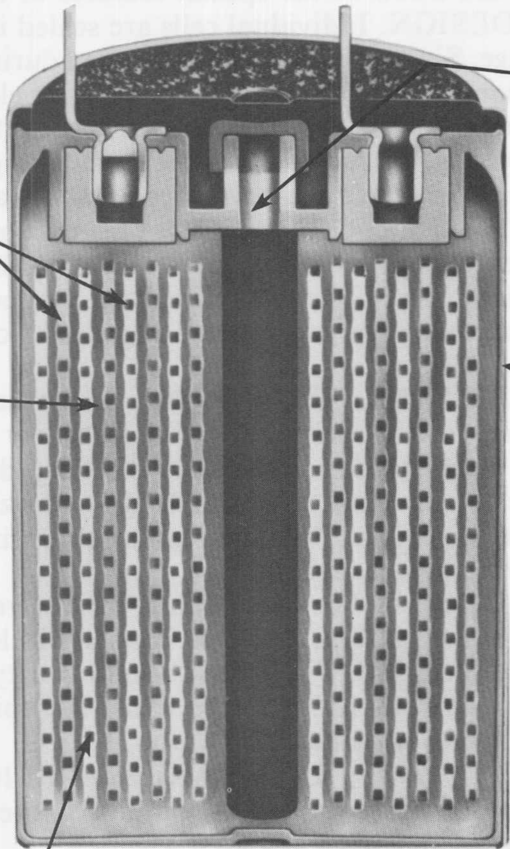
Storage Time

Ta = 0° C	7,200 days
Ta = 23° C	1,200 days
Ta = 65° C	60 days

SAFETY.
You have virtually no problems with thermal runaway caused by overcharging.

WIDE RANGE OF DISCHARGE RATES.
You get the option of high discharge rates due to very low internal impedances — greater than 100 amps from the D cell and 200 amps from the X cell are possible for short periods of time.

Construction features.



SECTION 1

INTRODUCTION

The purpose of this manual is to describe the characteristics of the Gates sealed lead-acid rechargeable cell in its many different applications. The unique design of the Gates cell overcomes many of the former limitations of the lead-acid system. At the same time, it retains the low cost, reliability, ruggedness and long life which have always been assets of the lead-acid battery. Here are a few of the special features of the Gates cell:

A TRULY SEALED DESIGN. Individual cells are sealed in a case to prevent acid, acid vapor, and water leakage. Since the cell can be operated during its normal life without loss of water, even during continuous overcharge, no water or electrolyte checks are ever required. The cell can be oriented in any direction in acceleration fields of several g's without alteration of its electrical characteristics. The sealed design even allows the cell to be operated in a vacuum or at elevated temperatures without failure.

LOW TEMPERATURE PERFORMANCE. The exceptional low temperature performance of the lead-acid system has been maintained in the Gates cell by use of a separator system which minimizes diffusion and resistance effects. This results in good utilization of active material and excellent voltage regulation over a wide temperature range.

HIGH-RATE CAPABILITIES. The thin-plate construction of the Gates cell contributes to high utilization of the active plate materials, low internal impedance, and minimal polarization. This means that the cell can be discharged at high rates with power densities up to 300 watts per pound. Thus, an outlandishly-oversized battery is not required for short duration, high-rate discharge. Voltage regulation during discharge and during changes in discharge current is also excellent.

Another advantage of this special construction is the fast recharge capability of the Gates cell. It is possible to recharge the cell to full capacity in less than one hour.

LONG LIFE IN FLOAT APPLICATIONS. The high purity of the lead grids used in the Gates cell result in long life on float charge while the spiral-wound plate design maintains structural resistance to shock and vibration.

LONG CYCLE LIFE IN DEEP-DISCHARGE APPLICATIONS. The spiral-wound plate design also reduces the rate of shedding of the positive plate, thereby increasing the cycle life at deep discharge levels.

STRUCTURAL RESISTANCE. The rugged metal case on the cell further enhances resistance to shock, crushing, or dropping.

PACKAGING FLEXIBILITY. The individual cell construction, in addition to the fact that these cells can be used in parallel for additional capacity, allows the battery to be laid out inside of the equipment in an almost infinite variety of patterns. Thus, much total space can be saved.

HIGH ENERGY DENSITY. The Gates cell has the highest energy and power density per unit volume of any lead-acid battery presently available. Most lead-acid cells have less than one watt hour per cubic inch, whereas the Gates cell has greater than 1.4 watt hours per cubic inch.

SECTION 2

CHEMISTRY OF THE GATES CELL

Although the design and construction of the Gates cell is totally unique, the overall chemistry is that of the traditional lead-acid battery. The basic "double sulfate" reaction is shown below:

$$1)\quad PbO_2 + Pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$$

The reaction at the positive electrode:

$$2)\quad PbO_2 + 3H^+ + HSO_4^- + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2H_2O + PbSO_4$$

At the negative electrode:

$$3)\quad Pb + HSO_4^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} PbSO_4 + H^+ + 2e^-$$

When the cell is recharged, the primary reaction taking place is as Equation 1. Finely-divided particles of $PbSO_4$ are being electrochemically-converted to sponge lead at the negative electrode and PbO_2 at the positive by the charging source-driving current through the battery. As the cell approaches complete recharge, where the majority of the $PbSO_4$ has been converted to Pb and PbO_2, the overcharge reactions begin. For the typical lead-acid cells, the result of these reactions is the production of hydrogen and oxygen gas and subsequent loss of water.

A unique aspect of the Gates cell is that the majority of the oxygen generated within the cell on overcharge (up to the C/3 rate) is recombined within the cell. The pure lead grids used in the construction minimize the evolution of hydrogen on overcharge. Although most of the hydrogen is recombined within the cell, some is released to the atmosphere.

Oxygen will react with lead at the negative plate in the presence of H_2SO_4 as quickly as it can diffuse to the lead surface. Hydrogen will be oxidized at the PbO_2 surface of the positive plate at a somewhat lower rate, as shown in Equations 4 and 5.

Overcharge Recombination Reactions:

$$4)\quad Pb + HSO_4^- + H^+ + 1/2O_2 \rightleftharpoons PbSO_4 + H_2O$$

$$5)\quad PbO_2 + HSO_4^- + H^+ + H_2 \rightleftharpoons PbSO_4 + 2H_20$$

In a flooded lead-acid cell, this diffusion of gasses is a slow process and virtually all of the H_2 and O_2 escape from the cell rather than recombine.

In the Gates cell, the closely spaced plates are separated by a glass mat separator which is composed of fine glass strands in a porous structure. The cell is filled with only enough electrolyte to coat the surfaces of the plates and the individual glass strands in the separator, thus creating the "starved electrolyte" condition. This condition allows for the homogeneous gas transfer between the plates, necessary to promote the recombination reactions.

The pressure release (Bunsen) valve maintains an internal pressure of 40-60 psi. This condition aids recombination by keeping the gases within the cell long enough for diffusion to take place. The net result is that water, rather than being released from the cell, is electrochemically-cycled to take up the excess overcharge current beyond what is used for conversion of active material. Thus the cell can be overcharged sufficiently to convert virtually all of the active material without loss of water, particularly at recommended recharge rates.

At continuous high overcharge rates (e.g., C/3 and above), gas buildup becomes so rapid that the recombination process is not as highly efficient and O_2 as well as H_2 gas is released from the cell.

SECTION 3

GATES CELL CONSTRUCTION

A breakdown of the basic components contained in the cell is shown in Figure 1.

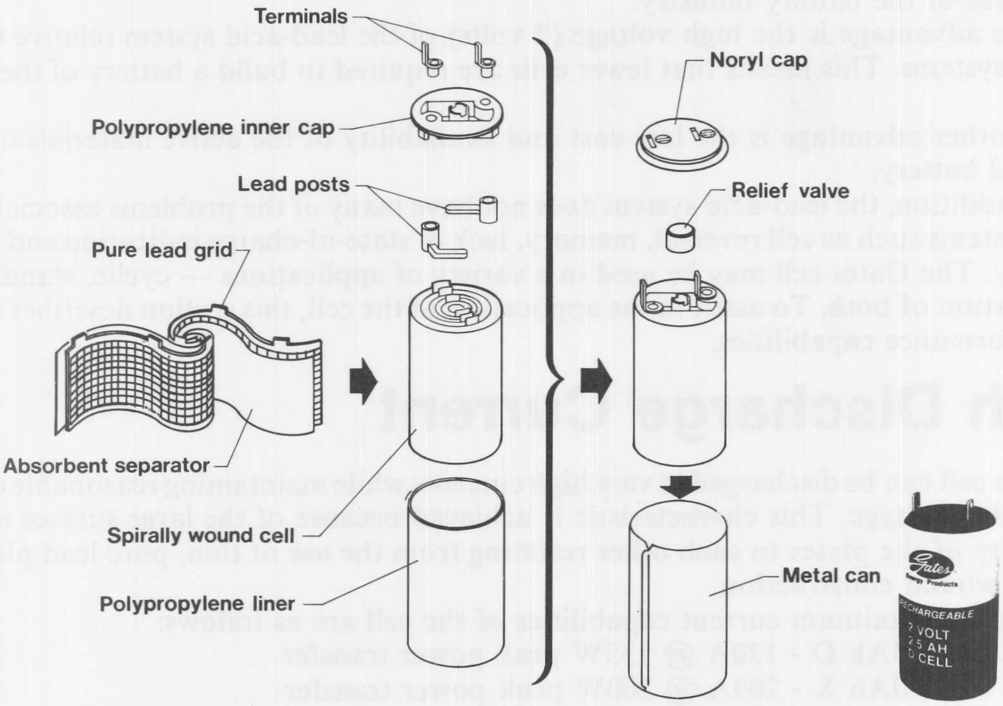


Figure 1 Cell Construction

Both the positive and negative plates are made of pure lead and are extremely thin. The plates are pasted with lead oxides, separated by an absorbing glass mat separator and spirally-wound to form the basic cell element. Lead posts are then welded to the exposed positive and negative plate tabs. The terminals are inserted through the polypropylene inner top and are effectively sealed by expansion into the lead posts. The element is then stuffed into the liner and the top and liner are bonded together. At this state of construction, the cell is sealed except for the open vent hole. Sulfuric acid is then added and the relief valve is placed over the vent hole. The sealed element is then inserted into the metal can, the outer plastic top added and crimping completes the assembly. The metal case is for mechanical strength and does not affect the operation of the resealable vent. The cell is now charged for the first time or electrochemically formed.

SECTION 4

PERFORMANCE CHARACTERISTICS

While overcoming certain problems associated with the traditional lead-acid cell, the Gates cell has retained the advantages which have made the traditional lead-acid cell the workhorse of the battery industry.

One advantage is the high voltage (2 volts) of the lead-acid system relative to other battery systems. This means that fewer cells are required to build a battery of the desired voltage.

Another advantage is the low cost and availability of the active materials used in a lead-acid battery.

In addition, the lead-acid system does not have many of the problems associated with other systems such as cell reversal, memory, lack of state-of-charge indication and thermal runaway. The Gates cell may be used in a variety of applications — cyclic, standby, or a combination of both. To assist in the application of the cell, this section describes some of the performance capabilities.

High Discharge Current

The cell can be discharged at very high currents while maintaining reasonable capacity at a usable voltage. This characteristic is achieved because of the large surface area and proximity of the plates to each other resulting from the use of thin, pure lead plates in a spirally wound construction.

Typical maximum current capabilities of the cell are as follows:

2V 2.5Ah D - 130A @ 135W peak power transfer
2V 5.0Ah X - 200A @ 200W peak power transfer
2V 25Ah BC - 600A @ 600W peak power transfer

Low Temperature Characteristics

Exceptional low temperature characteristics are maintained through the use of a separator system which minimizes the resistance and diffusion effects. This results in efficient utilization of active materials and excellent voltage regulation.

Because the cell operates as a "starved" electrolyte system, there is only enough electrolyte to maintain the rated capacity of the cell. With this minimal amount of electrolyte, the cell will not be damaged at temperatures as low as -65° C, even if stored at that temperature in a discharged state.

Capacity available at low temperatures is a function of both the temperature and discharge current. For various discharge rates and temperature curves, refer to Section 5.

Position Flexibility

With the starved electrolyte system, the sulfuric acid is absorbed within the cell plates and the glass mat separator. The cell is virtually dry with no loose electrolyte allowing it to be charged, discharged, or stored in any position without electrolyte leakage.

Sealed Design

One of the most important features of the Gates cell is its sealed operation. This mode of operation is possible because the cell is able to use the oxygen cycle during overcharge.

The oxygen, which is evolved at the positive electrode when the cell is overcharged, is recombined at the negative electrode. Hydrogen evolution is minimized by balancing the materials in the electrodes so the positive electrode will become fully-charged and start evolving oxygen before the negative electrode is completely charged. A self-resealing valve is provided as a safety feature in case of misapplication or abuse of the cell.

It is important to distinguish between a sealed cell, such as the Gates cell, and the so-called "maintenance-free" cell made by several manufacturers. In a "maintenance-free" system, the cell is vented to allow escape of gases formed from the decomposition of the water in the electrolyte during overcharge. Thus, water is lost from the cell when the cell is overcharged. Since no water can be added to the cell, life is dependent on the initial amount of water in the cell.

The sealed Gates cell is truly maintenance-free in that no water need be added to the cell during its operation. The life of the cell is not dependent on the initial concentration of water in the cell as with other so-called maintenance-free systems.

Shock and Vibration Characteristics

The spirally-wound plate element is compressed within the polypropylene liner, minimizing plate movement in high shock or vibration applications. Movement in a vertical direction is also limited by the polypropylene top design. Overall, the cell has excellent shock and vibration characteristics.

Float Life Characteristics

As noted previously, the life expectancy of the Gates cell is not limited by loss of electrolyte, due to the sealed design. Instead, life expectancy is determined by long-term corrosion at the positive plate. The corrosion effect on cell capacity is minimal until the cell approaches end-of-life, which is defined as the cell providing less than 80% of its rated capacity.

Major factors determining float life are temperature and float voltage, as discussed further in Section 9.

Cycle Life Characteristics

The life of the cell in a cyclic application will be a function of the following variables: depth-of-discharge, temperature and charging rate. Cycle life can vary from 200 to greater than 2,000 cycles, dependent upon the depth-of-discharge, as shown on the life curves in Section 9.

Fast Charging Characteristics

Efficient, fast-charging can be accomplished using a constant voltage type charger. With initial charge current capability in the 5C range, the cell can be recharged in less than one hour.

Further specifics on fast-charging are given in Section 7.

Storage Characteristics

The Gates cell may be stored for three years at room temperature and recharged with no loss in cell reliability or performance capabilities.

Storage time is essentially a function of temperature. A curve showing the time-temperature relationship is in Section 6.

SECTION 5

DISCHARGE CHARACTERISTICS

Figures 1 through 5 are typical discharge voltage curves as a function of time at various ambient temperatures ranging from −40°C to +65°C for various discharge rates for the D and X cells. The "C" indicates the battery capacity in amp hours; e.g., a C/10 discharge is 250ma for the 2.5Ah D cell and 500ma for the 5Ah X cell. (A further definition of C/X rate is in the glossary.)

With the Gates cell, the capacity increases as the temperature increases. Capacity also increases as the discharge rate decreases, as in most battery systems.

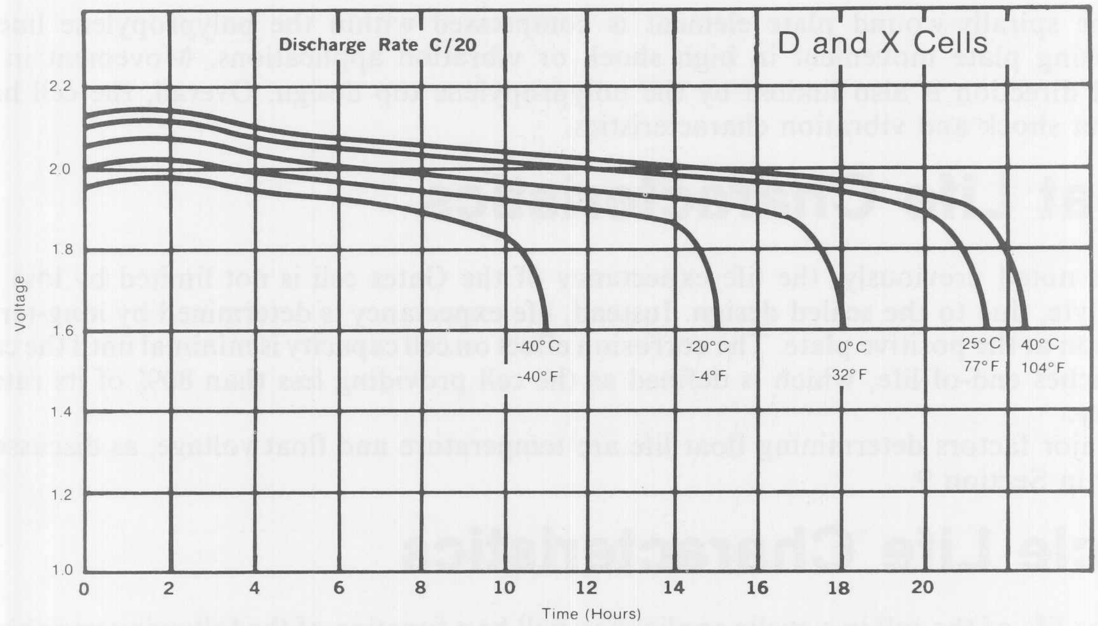


Figure 1

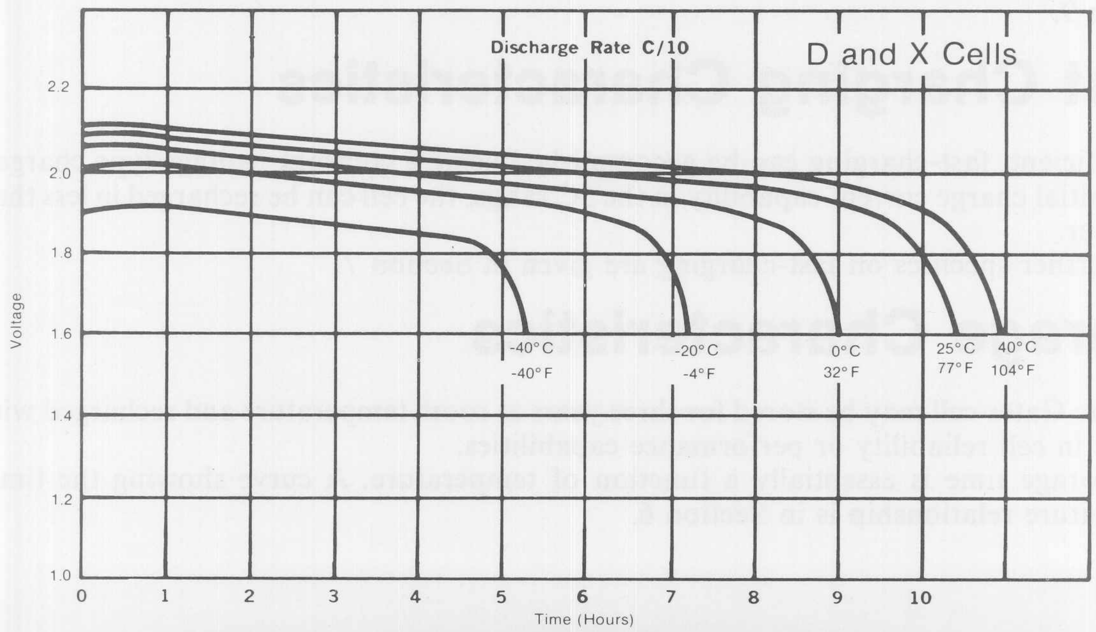


Figure 2

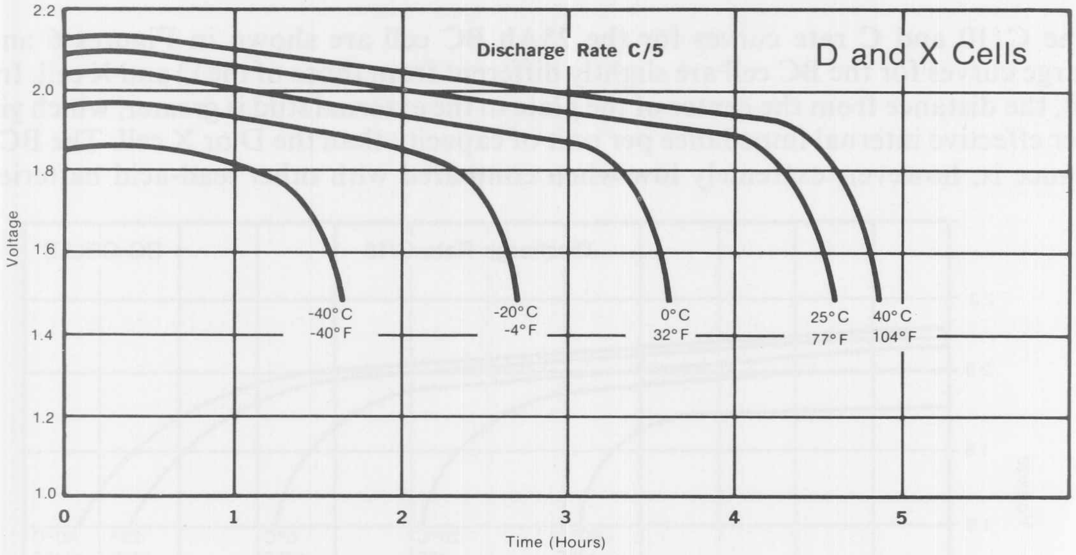


Figure 3

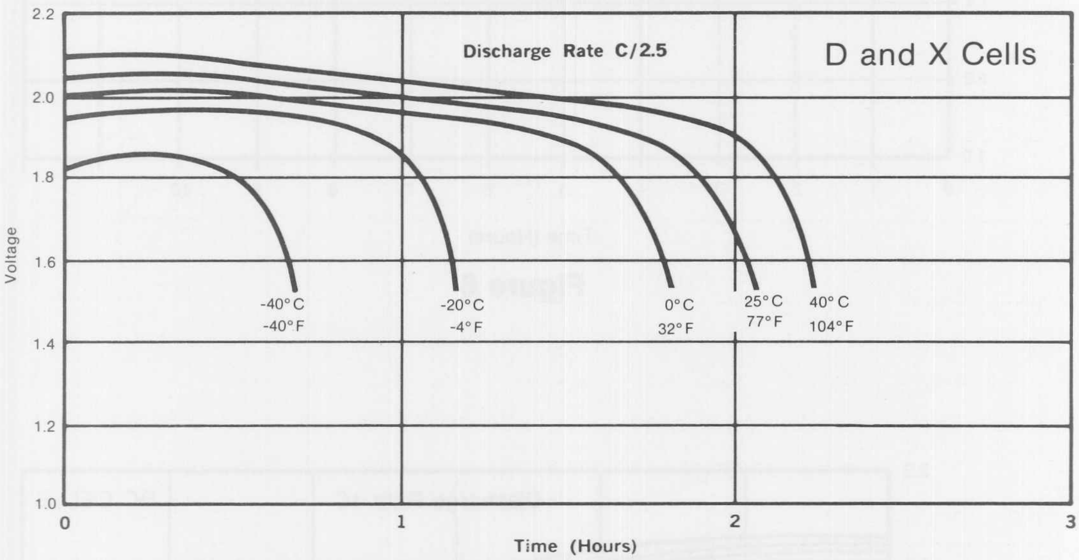


Figure 4

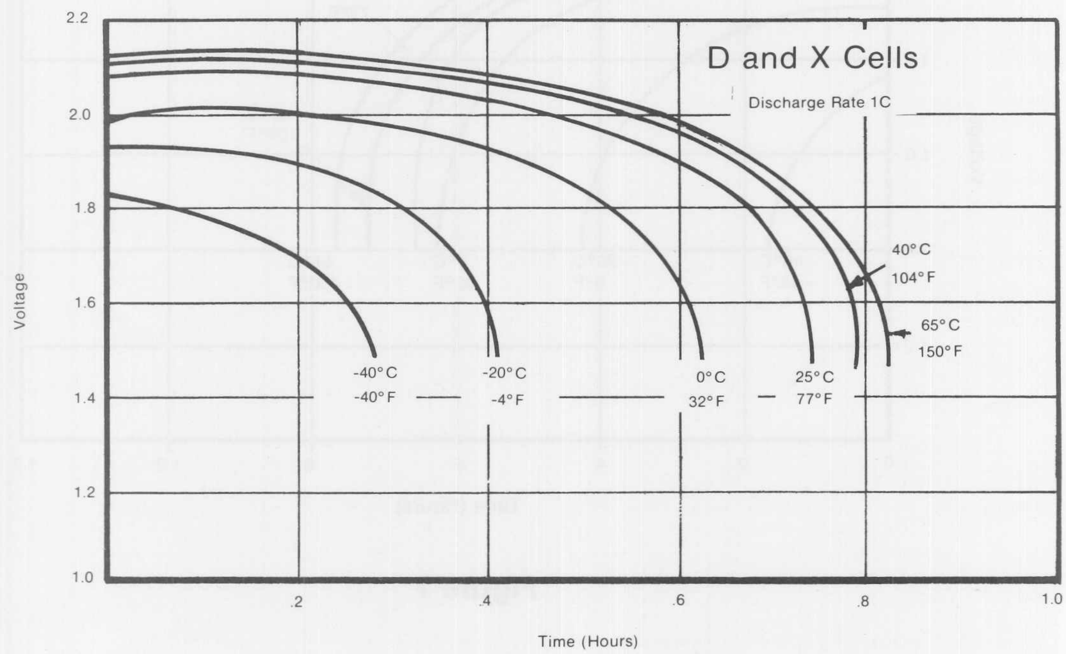


Figure 5

The C/10 and C rate curves for the 25Ah BC cell are shown in Figures 6 and 7. Discharge curves for the BC cell are slightly different from those of the D and X cell. In the BC cell, the distance from the center of the plate to the external stud is greater, which yields a higher effective internal impedance per unit of capacity than the D or X cell. The BC cell impedance is, however, extremely low when compared with other lead-acid batteries.

Figure 6

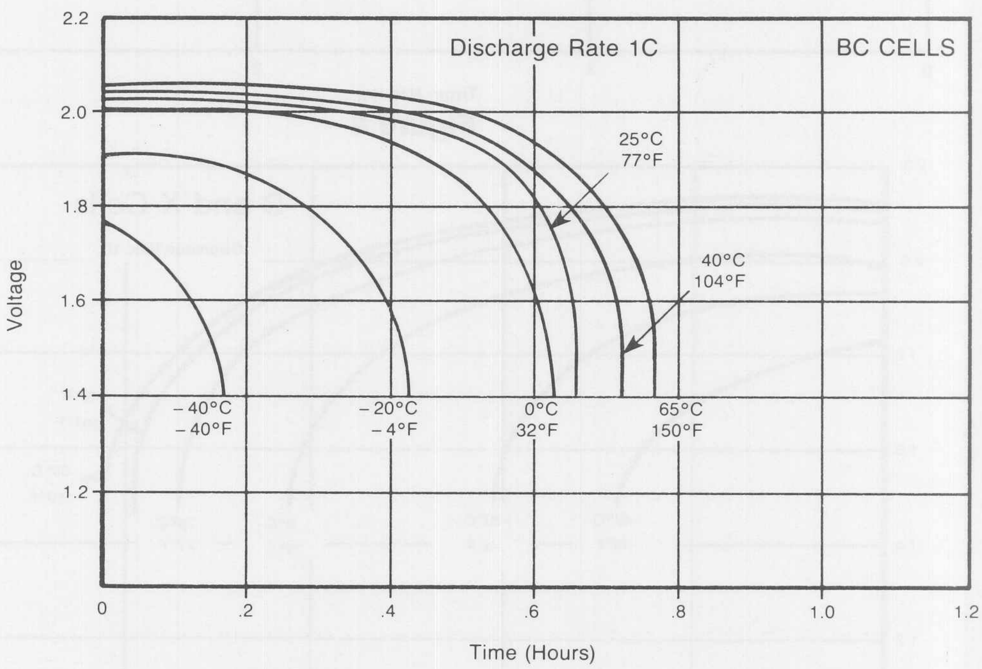
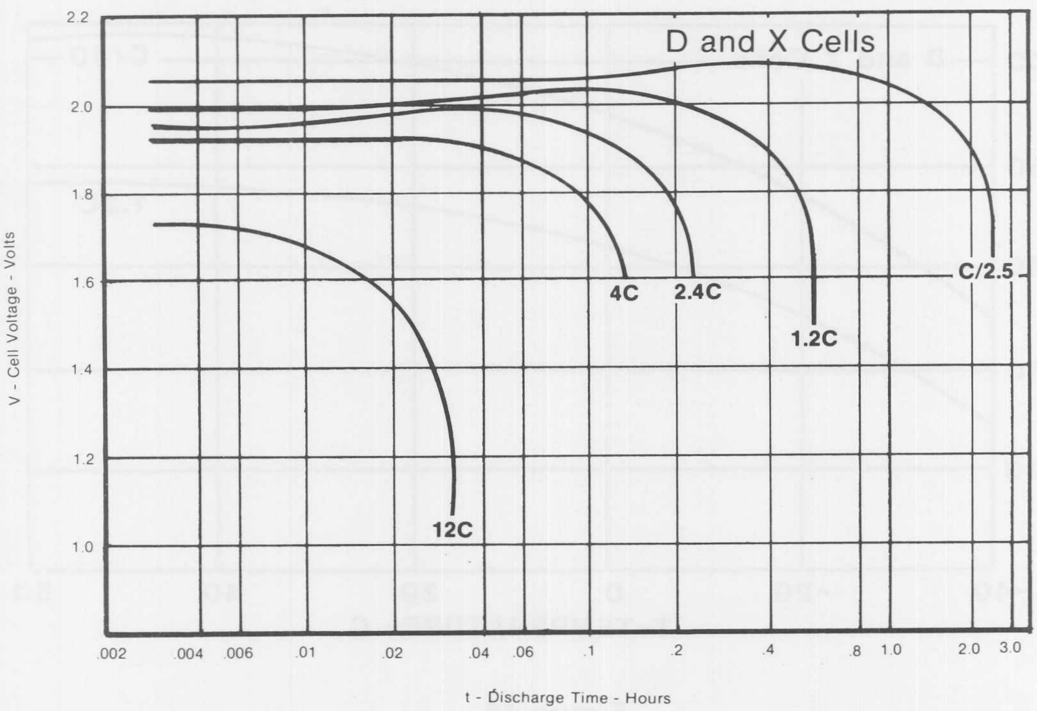


Figure 7

Voltage discharge profiles of various discharge currents at room temperature are shown in Figures 8 and 9. As shown, the initial discharge voltage decreases as the discharge current increases, although to a lesser extent than some battery types.



Voltage Regulation

Figure 8

Figure 9

Capacity of the Gates cell is dependent upon both the ambient temperature and discharge rate. Percentage of capacity available will be higher at a given temperature at lower discharge rates, with effects shown at the C/10 and 1.2 C rate in Figures 10 and 11.

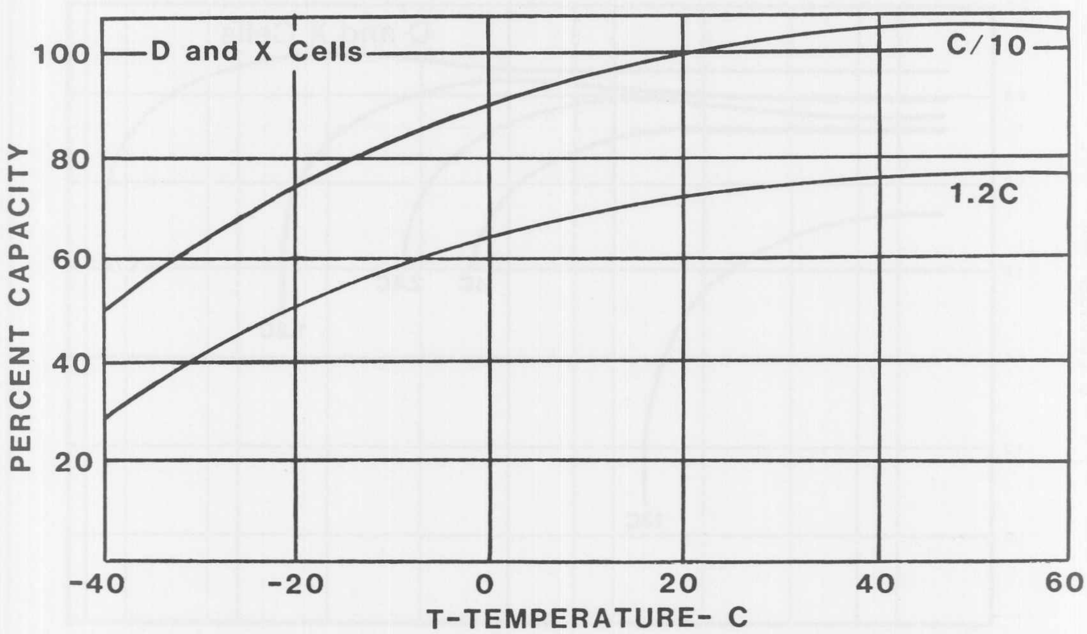


Figure 10

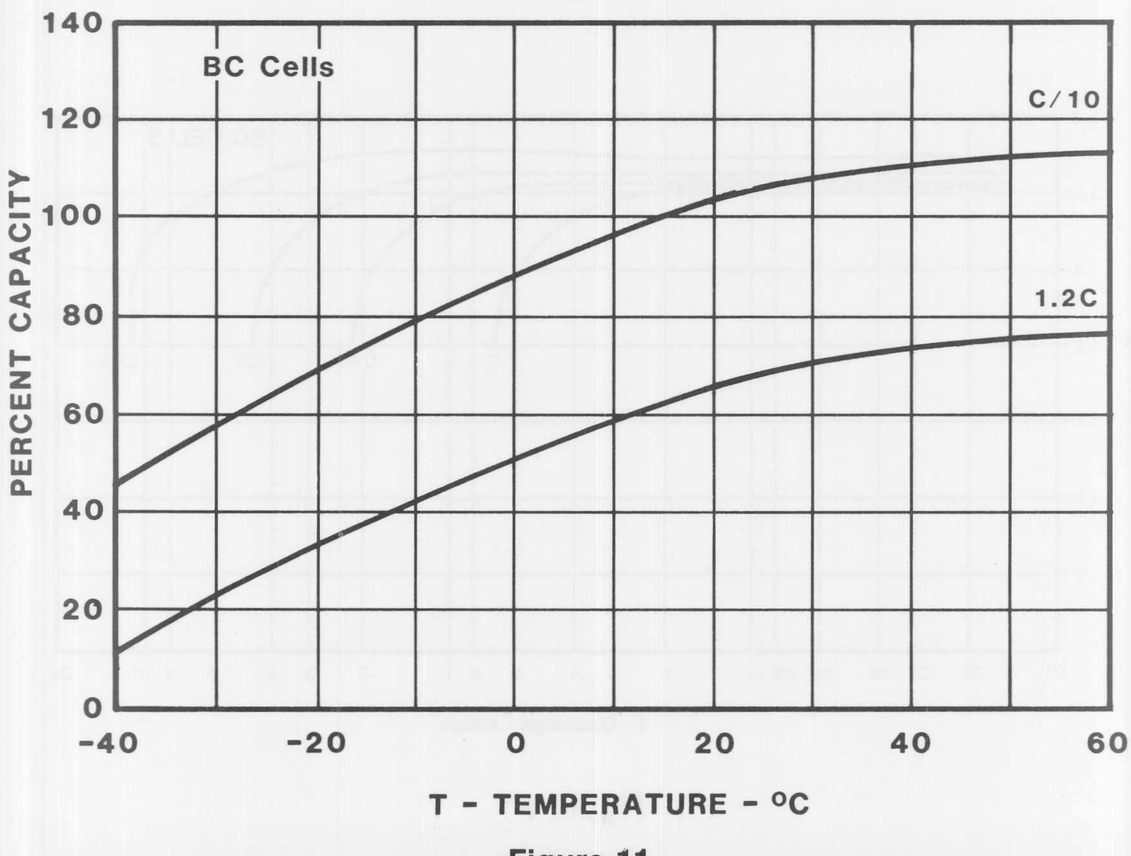


Figure 11

High Rate Pulse Discharge

The Gates cell is especially effective in applications which require a high-rate pulse discharge, such as in engine starting. In Figure 12, the voltage-time curves are shown for the Gates cell at room temperature at the 10C discharge rate both on continuous discharge and for a 16.7% duty cycle (10 second pulse, 50 second rest).

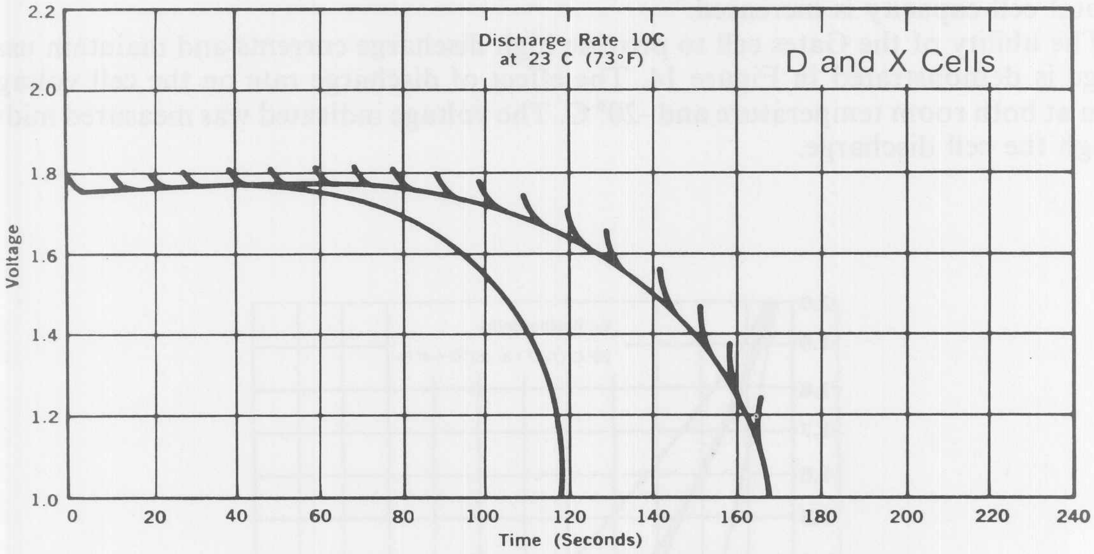


Figure 12

Figure 13 illustrates analogous curves at -20° C. At all temperatures, the Gates cell performs better than any other commercially available lead-acid cell.

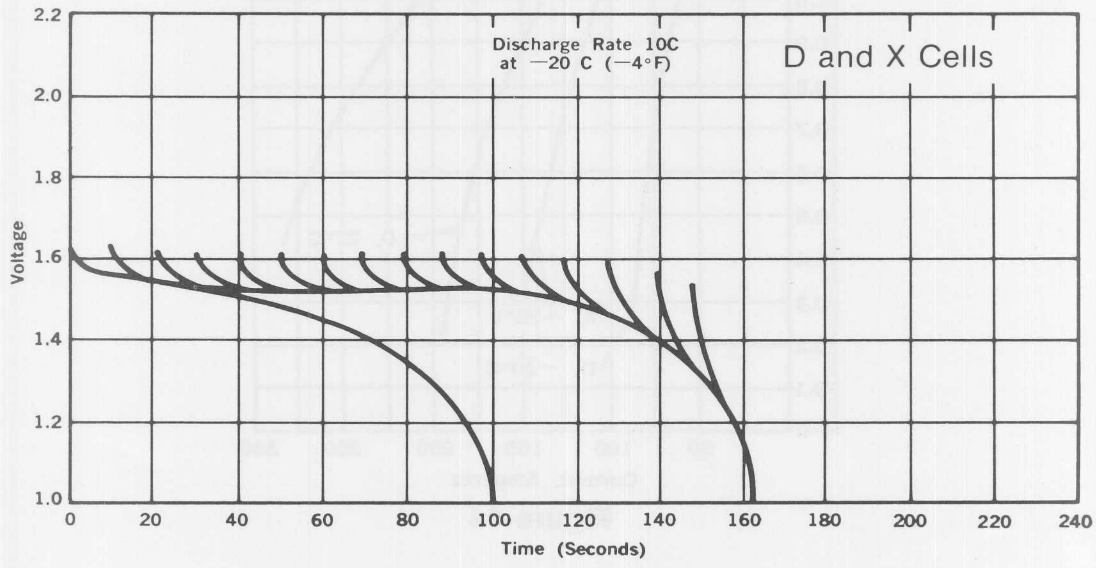


Figure 13

It is apparent from these data that the capacity of the Gates cell is increased greatly when a pulse discharge is used. This is true because of the phenomenon known as "concentration polarization," which occurs during discharge. As a discharge current is drawn from the cell, the sulfuric acid in the electrolyte reacts with the active materials in the electrodes. This reaction reduces the concentration of the acid at the electrode-electrolyte interfaces. Consequently, the cell voltage drops. During the rest period, the acid in the bulk of the solution diffuses into the electrode pores to replace the acid which has been used up. The cell voltage now increases as acid equilibrium is established. Since during a pulse discharge the acid is allowed to equilibrate between pulses, it is not depleted as quickly and the total cell capacity is increased.

The ability of the Gates cell to provide high discharge currents and maintain usable voltage is demonstrated in Figure 14. The effect of discharge rate on the cell voltage is shown at both room temperature and -20° C. The voltage indicated was measured midway through the cell discharge.

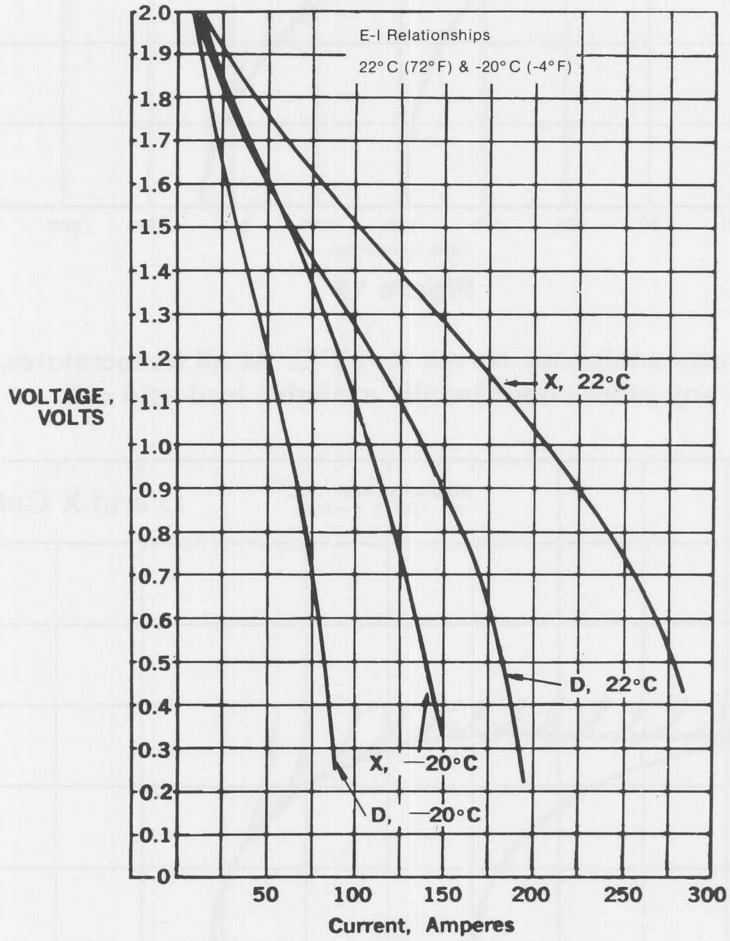


Figure 14

The curves in Figure 15 illustrate the power of the cell as a function of discharge rate at room temperature and -20° C. Maximum power obtainable from the Gates cell increases as the temperature increases.

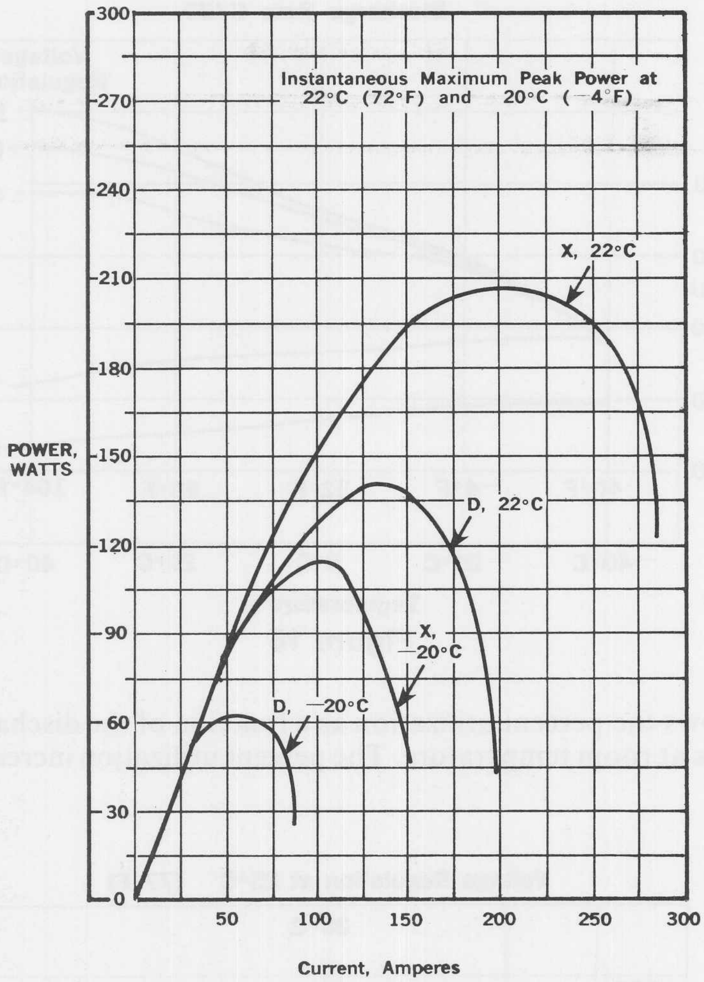


Figure 15

Voltage Regulation

In many applications, voltage regulation is an important aspect of cell performance. The voltage regulation of the Gates cell is equal to or better than that of any other secondary battery system available. It can be seen from the curves in Figures 1 - 7 that the voltage remains nearly constant throughout the discharge. In Figure 16, the percent utilization is shown as a function of the temperature for various voltage regulations at the C/20 discharge rate. The percent utilization is defined by the equation:

$$\%\ U = \frac{C_f}{C_r} \times 100$$

for the Gates cell, where Cf is the capacity obtained from the cell to the cutoff point and Cr is the rated capacity at the C/10 rate at room temperature. Voltage regulation is defined as:

$$VR = 2\left(\frac{V_{max} - V_{min}}{V_{max} + V_{min}}\right)$$

where Vmax is the maximum voltage and Vmin is the cutoff voltage for each specific curve. The percent utilization decreases as the temperature decreases because the internal impedance is increased at lower temperatures.

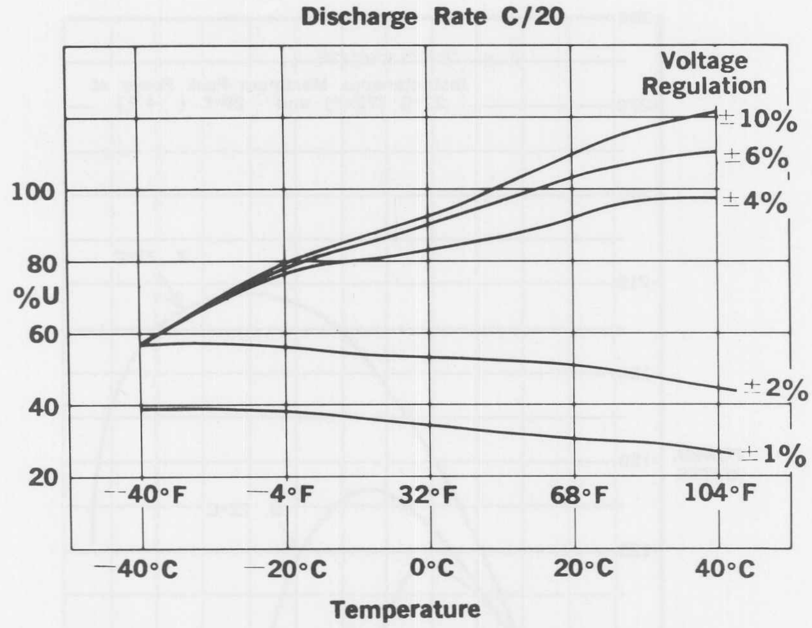


Figure 16

Figure 17 shows the percent utilization as a function of the discharge rate for various voltage regulations at room temperature. The percent utilization increases as the discharge rate decreases.

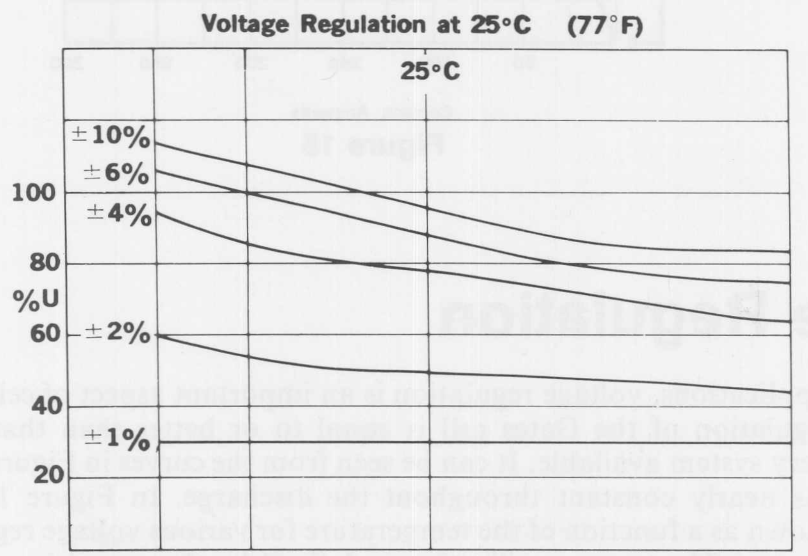


Figure 17

Discharge Level

The voltage point at which 100% of the usable capacity of the cell has been removed is a function of the discharge rate. For optimum cell life, it is recommended that the cell be disconnected from the load at this end-voltage point.

The shaded area in Figure 18 represents the recommended disconnect voltage for various rates of discharge. The upper portion of the shaded area represents the point at which 100% of the available capacity is removed. The lower portion represents the minimum voltage the cell should be discharged to at given rates of discharge. The cell should be disconnected from the load when voltage is within the shaded area for optimum cell life.

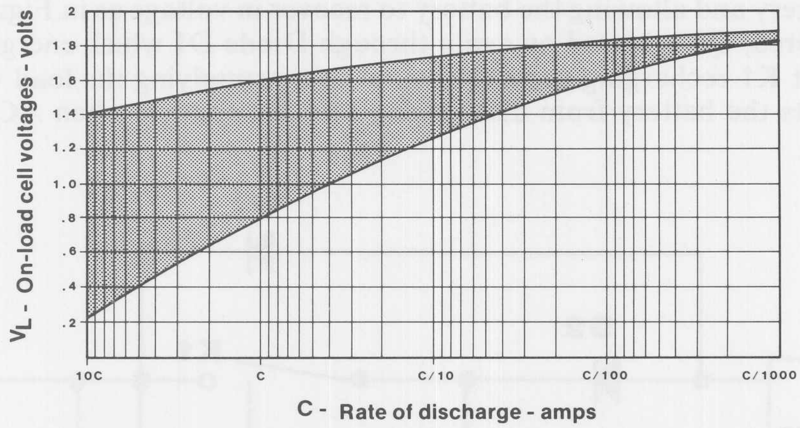


Figure 18

Discharging the Gates cell below these voltage levels or leaving the cell connected to a load in a discharged state will impair the ability of the cell to accept a charge.

Under these "over-discharge" conditions, the sulfuric acid electrolyte can be depleted of the sulfate ion and become essentially water, which can create several problems. A lack of sulfate ions as charge conductors will cause the cell impedance to appear high and little charge current to flow. Longer charge time or alteration of charge voltage may be required before normal charging may resume.

Another potential problem is lead sulfate's solubility in water. In a severe deep discharge condition, the lead sulfate present at the plate surfaces can go into solution in the water electrolyte. Upon recharge, the water and sulfate ion in the lead sulfate convert to sulfuric acid, leaving a precipitate of lead metal in the separator. This lead metal can result in dendritic shorts between the plates and resultant cell failure.

As noted previously, disconnecting the battery from the load as indicated in Figure 18 will totally eliminate the over-discharge problems and allow the cell to provide its full cycle life and charge capabilities.

Voltage Recovery Effects

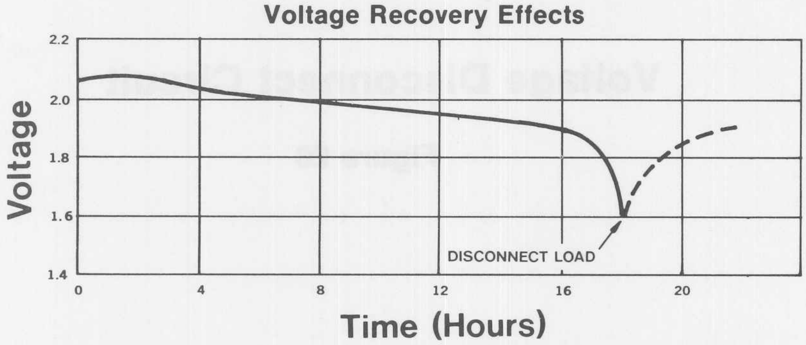
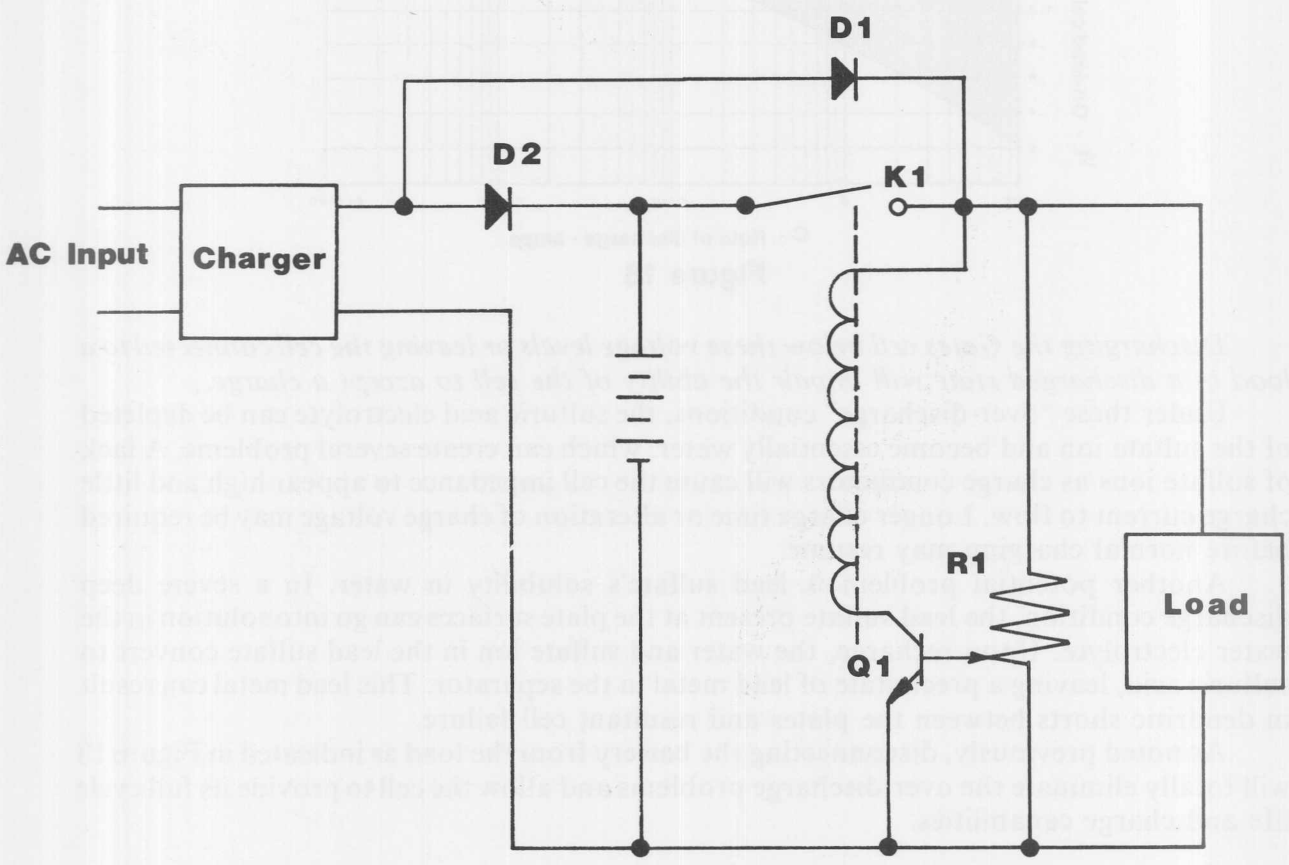


Figure 19

It is important to note that when the load is removed from the cell, the cell voltage will increase — up to approximately 2 volts. Figure 19 is an example of a C/16 discharge rate with removal of the load at a cell voltage of 1.6 volts showing subsequent recovery of the cell voltage. Because of this phenomenon, some hysteresis must be designed into the battery-disconnect circuitry so that the load is not continuously reapplied to the battery as the battery voltage recovers.

Figure 20 is an example of a typical circuit which could be used in some applications to disconnect the battery from the load after discharge. In the example, the battery is being continuously float-charged when the AC source is available and the load is being supplied from the charger and battery through relay contacts K1. When AC power fails, the battery supplies all of the current to the load. As the battery voltage drops, base current to Q1 drops through resistor R1 until Q1 is biased off and relay contacts K1 open, disconnecting the load from the battery and allowing the battery to recover in voltage as in Figure 19. When AC power is restored, Q1 is biased on again through Diode D1 which energizes the relay and closes contact K1 recharging the battery and again supplying the load with current. Diode D2 prevents the battery from discharging into the charger when AC has failed.



Voltage Disconnect Circuit

Figure 20

STORAGE CHARACTERISTICS

State of Charge

The state of charge of the Gates cell can be approximated by use of Figure 1 (OCV vs. SOC).

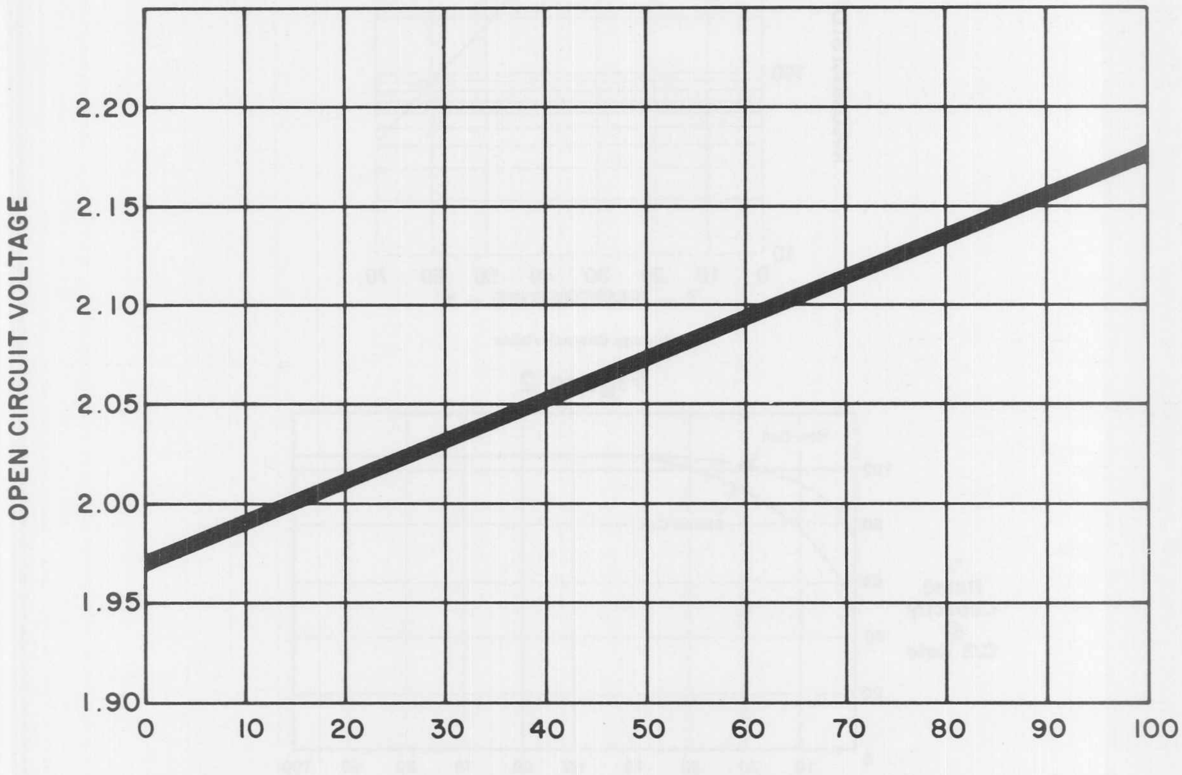


Figure 1

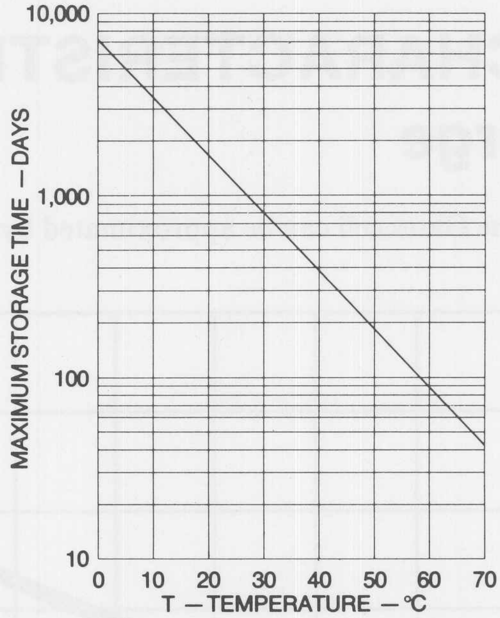
This curve is accurate to within 20% of the capacity of the cell being measured, if it has not been charged or discharged within the past 24 hours. The curve is accurate to within 5%, if the cell has not been charged or discharged within the past 5 days. The capacity, as taken from Figure 1, is the capacity available at the C/10 rate of discharge. The measurement of the open circuit voltage of a cell to determine the state of charge is based on the relationship between the electromotive force (OCV) and the concentration (specific gravity) of the sulfuric acid in the battery.

Storage

Most batteries lose their stored energy when allowed to stand on open circuit due to the fact that the active materials are in a thermally unstable state. The rate of self-discharge is dependent on the chemistry of the system and the temperature at which it is stored.

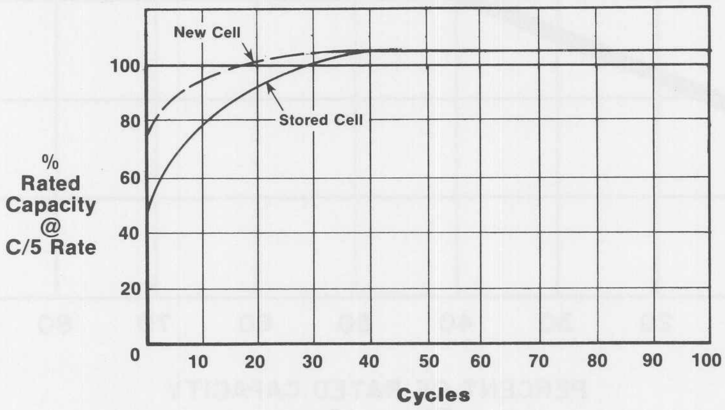
The Gates cell is capable of long storage without damage as can be seen in Figure 2, which is a curve of maximum storage time vs. temperature. This curve shows the maximum number of days at any given temperature from 0° to 70° C for the cell to discharge from

2.18 volts down to 1.81 volts open circuit. The cell should not be allowed to self-discharge below 1.81 volts, because the recharge characteristics of the cell change appreciably and the cycle life cannot be accurately predicted.



Storage Characteristics

Figure 2



Capacity Characteristics After Storage

Figure 3

Figure 3 is a curve of percent rated capacity vs. cycles which shows the recovery of capacity of cells allowed to self-discharge to approximately 1.85V open circuit. These cells were then cycled at 1 cycle per day using a constant voltage charge of 2.5V and a C/5 rate discharge to 1.6V. Many tests have been run which allowed cells to self-discharge down to 1.81 volts. These cells were then recharged and observed to cycle normally. The first charge on a cell which has been allowed to self-discharge down to 1.81 will take longer than normal and the first discharge will generally not deliver rated capacity. Subsequent cycles, however, will show an increase in the cell capacity to rated value.

It is important to recognize that the self-discharge rate of the Gates sealed lead-acid cell is nonlinear; thus the rate of self-discharge changes as the state of charge of the cell changes. When the cell is in a high state of charge, i.e., 80% or greater, the self-discharge is very rapid. The cell may discharge from 100% to 90% at room temperature in a matter of a week or two. Conversely, at the same temperature, it may take 10 weeks or longer for the same cell to self-discharge from 20% state of charge down to 10% state of charge. Figure 4 is a curve of open circuit voltage vs. percent remaining storage time that shows the non-linearity of the self-discharge reaction.

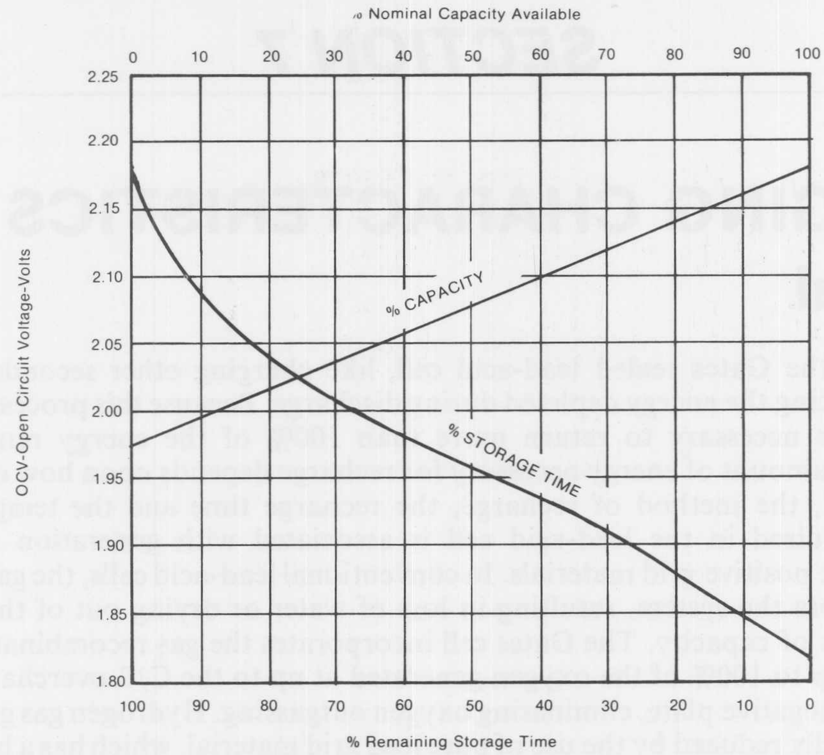


Figure 4

By the use of Figures 2 and 4, the number of days of storage can be calculated which remain before a cell must be recharged. As an example, if a cell has an OCV of 2.05 volts, the state of charge, as determined from Figure 4 is 35%. From Figure 4 (again at OCV of 2.05V), the remaining storage time is 82%. Figure 2 shows that at 20° C, the cell can be stored for a total of 1,200 days before it must be recharged. Therefore, the remaining storage time is 82% of 1,200, or 984 days. This is the number of days that a cell at 2.05 volts OCV can be stored before it will reach 1.81 volts and must be recharged.

The Gates cell is capable of being self-discharged to these extremely low voltages and returned to full capacity because of its unique electrolyte-limited design.

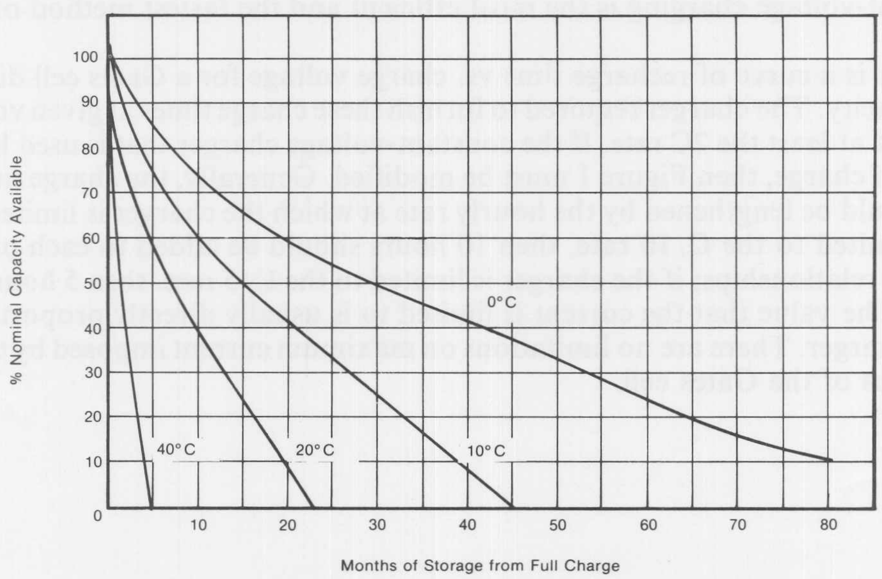


Figure 5

Figure 5 is a curve of the remaining usable capacity in a Gates cell vs. months of storage at various temperature. This curve is convenient in determining the approximate remaining capacity after a given storage time at a temperature.

CHARGING CHARACTERISTICS

General

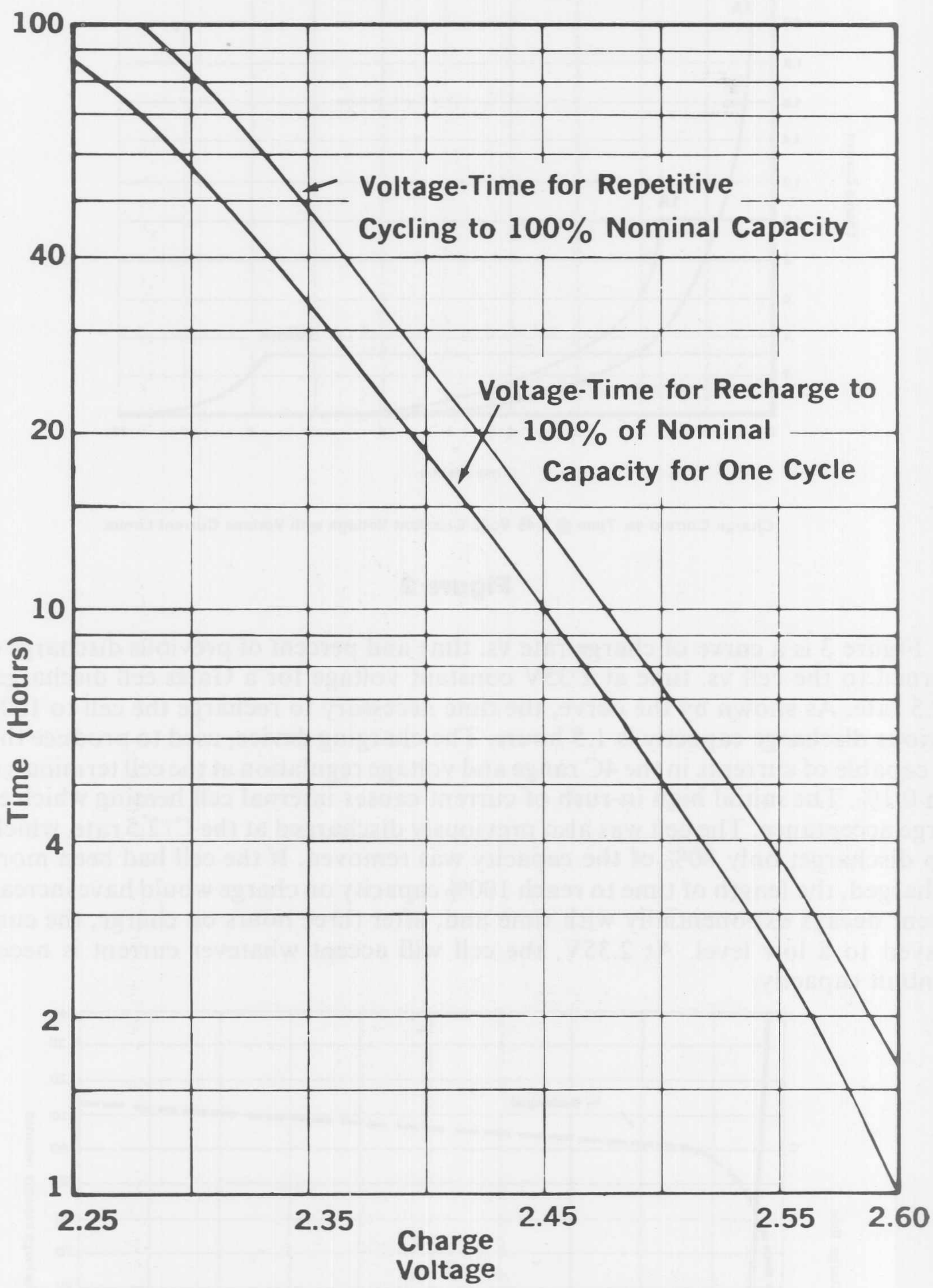
Charging the Gates sealed lead-acid cell, like charging other secondary cells, is a matter of replacing the energy depleted during discharge. Because this process is somewhat inefficient, it is necessary to return more than 100% of the energy removed during discharge. The amount of energy necessary for recharge depends upon how deeply the cell was discharged, the method of recharge, the recharge time and the temperature. The overcharge required in the lead-acid cell is associated with generation of gases and corrosion of the positive grid materials. In conventional lead-acid cells, the gases generated are released from the system, resulting in loss of water or drying out of the system and subsequent loss of capacity. The Gates cell incorporates the gas recombination principle which allows up to 100% of the oxygen generated at up to the C/3 overcharge rate to be reduced at the negative plate, eliminating oxygen outgassing. Hydrogen gas generation has been substantially reduced by the use of pure lead grid material, which has a high hydrogen overvoltage. The corrosion of the positive grid has been reduced by the use of pure lead. Also, the effects of corrosion of the positive grid have been minimized by the element construction.

Charging can be accomplished by various methods. The objective is to drive current through the cell in the direction opposite that of discharge. Constant-voltage charging is the conventional method for lead-acid cells and is also acceptable for the Gates cell. However, constant current, taper current, and variations thereof can also be used.

Constant-Voltage Charging

Constant-voltage charging is the most efficient and the fastest method of charging a Gates cell.

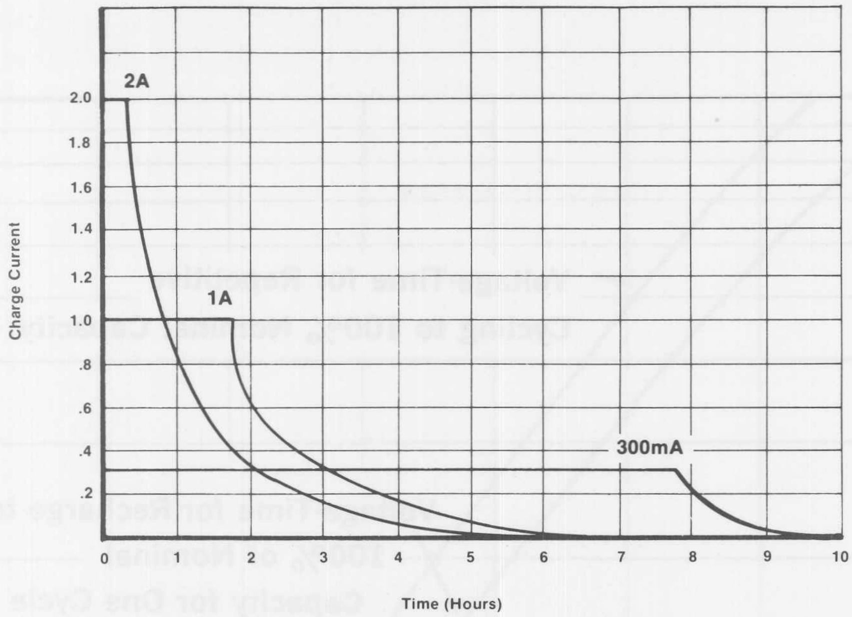
Figure 1 is a curve of recharge time vs. charge voltage for a Gates cell discharged to 100% of capacity. The charger required to furnish these charge times at given voltages must be capable of at least the 2C rate. If the constant-voltage charger that is used has less than the 2C rate of charge, then Figure 1 must be modified. Generally, the charge times given in Figure 1 should be lengthened by the hourly rate at which the charger is limited; i.e., if the charger is limited to the C/10 rate, then 10 hours should be added to each of the charge voltage-time relationships; if the charger is limited to the C/5 rate, then 5 hours should be added, etc. The value that the current is limited to is usually directly proportional to the cost of the charger. There are no limitations on maximum current imposed by the charging characteristics of the Gates cell.



Charge Voltage vs. Time on Charge at 23°C, 73°F.

Figure 1

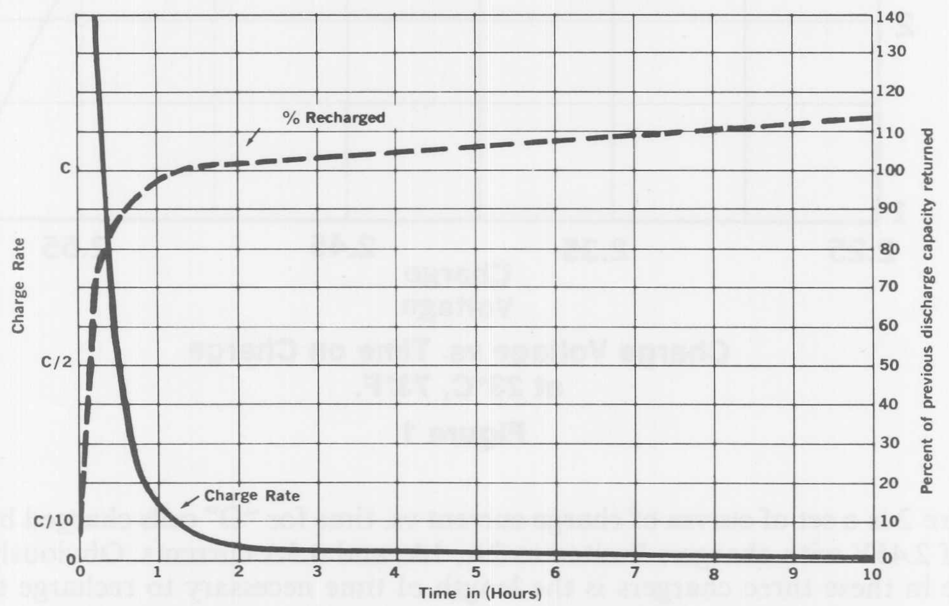
Figure 2 is a set of curves of charge current vs. time for "D" cells charged by constant voltage of 2.45V with chargers limited to 2A, 1A, and 0.3A currents. Obviously, the only difference in these three chargers is the length of time necessary to recharge the cell.



Charge Current vs. Time @ 2.45 Volts Constant Voltage with Various Current Limits

Figure 2

Figure 3 is a curve of charge rate vs. time and percent of previous discharge capacity returned to the cell vs. time at 2.35V constant voltage for a Gates cell discharged at the C/2.5 rate. As shown by the curve, the time necessary to recharge the cell to 100% of the previous discharge capacity is 1.5 hours. The charging device, used to produce this curve, was capable of currents in the 4C range and voltage regulation at the cell terminals of better than 0.1%. The initial high in-rush of current causes internal cell heating which enhances charge acceptance. The cell was also previously discharged at the C/2.5 rate, which is not a deep discharge; only 80% of the capacity was removed. If the cell had been more deeply discharged, the length of time to reach 100% capacity on charge would have increased. The current decays exponentially with time and, after three hours on charge, the current has decayed to a low level. At 2.35V, the cell will accept whatever current is necessary to maintain capacity.

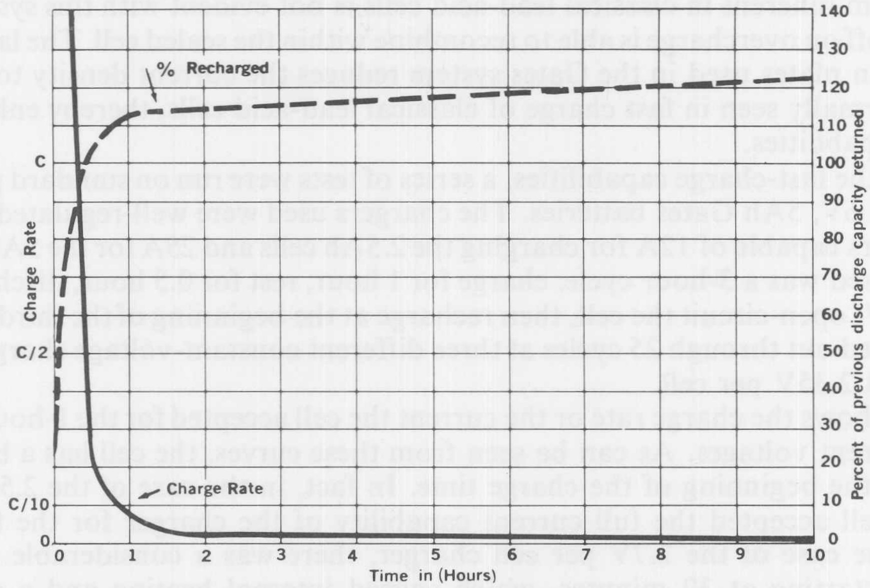


Charge rate and % recharged versus time during 2.35V. constant voltage charge at room temperature.

Figure 3

Figure 4 is a curve of charge rate vs. time and percent capacity vs. time for a cell charged at 2.50 volts constant voltage which has been previously discharged at the C/2.5 rate. Figure 4 shows that 100% of the capacity taken out on the previous discharge is returned to the cell in approximately one-half hour. The charger used with the Gates cell to produce the curve in Figure 4 was capable of a 6C output rate with constant-voltage regulation at the cell terminals better than 0.1%.

Figures 3 and 4 show the excellent charge acceptance of the Gates cell with a well-regulated, constant-voltage charger.



Charge rate and % recharge versus time during 2.50V constant voltage charge at room temperature.

Figure 4

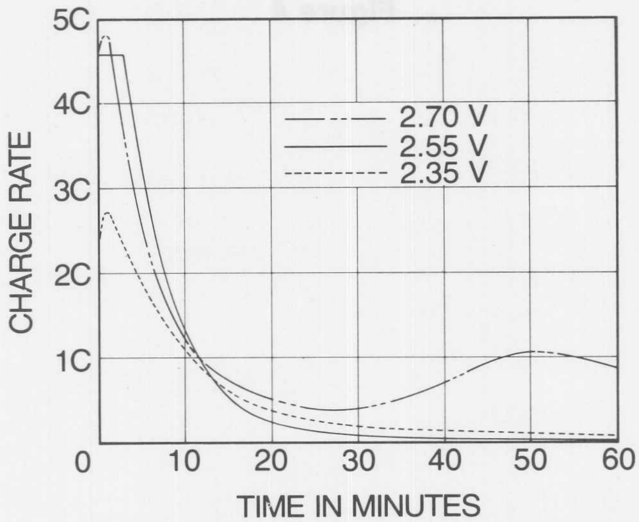
Fast Charging

A fast charge is defined as a method of charge which will return the full capacity of a cell in less than four hours. However, many typical applications require one hour or less. Prior to the development of the Gates sealed lead-acid system, commercially available lead-acid cells were restricted to charging times of greater than four hours.

Unlike classical parallel plate lead-acid cells, the Gates cell uses a starved electrolyte system where the majority of the electrolyte is contained within a highly retentive separator which then creates the starved plates necessary for homogeneous gas phase transfer. The gassing problem inherent in classical lead-acid cells is not evident with this system, as the oxygen given off on overcharge is able to recombine within the sealed cell. The large surface area of the thin plates used in the Gates system reduces the current density to a level far lower than normally seen in fast charge of classical lead-acid cells, thereby enhancing the fast-charge capabilities.

To study the fast-charge capabilities, a series of tests were run on standard production 6V, 2.5Ah and 6V, 5Ah Gates batteries. The chargers used were well-regulated, constant-voltage chargers capable of 12A for charging the 2.5Ah cells and 25A for the 5Ah cells. The cycle regime used was a 3-hour cycle: charge for 1 hour, rest for 0.5 hour, discharge at the 1C rate to 1.6V, open-circuit the cell, then recharge at the beginning of the third hour. This cycle was carried out through 25 cycles at three different constant-voltage charge voltages, 2.70, 2.55, and 2.35V per cell.

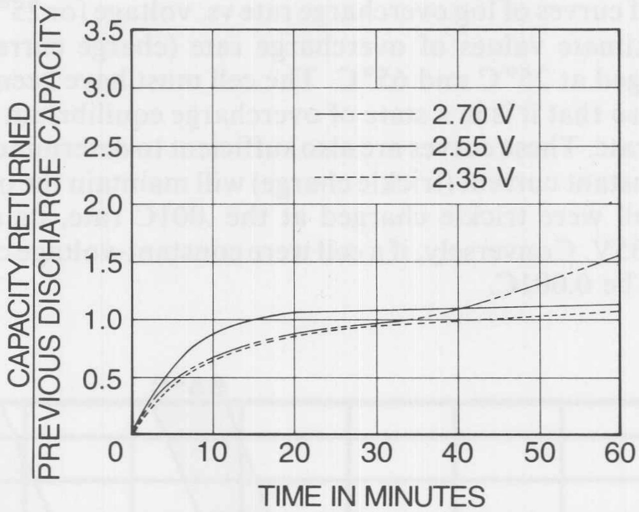
Figure 5 shows the charge rate or the current the cell accepted for the 1-hour charge at the three different voltages. As can be seen from these curves, the cell has a high charge acceptance at the beginning of the charge time. In fact, in the case of the 2.55V per cell charger, the cell accepted the full current capability of the charger for the first 3 to 4 minutes. In the case of the 2.7V per cell charger, there was a considerable amount of overcharging starting at 30 minutes, which caused internal heating and a consequent increase in charge current.



Charge rate versus time for three charge voltages.

Figure 5

Figure 6 is a set of curves of normalized charge efficiency vs. time in minutes for the three different voltages. This efficiency figure was calculated by dividing the total ampere-hour capacity returned, as in Figure 5, by the previous discharge capacity removed. This demonstrates a measure of the charging efficiency for this particular cycle. As can be seen from the curves, the 2.55V charger returned 100% of the capacity removed on the previous cycle in 15 minutes. The 2.7V charger had put a 60% overcharge into the cell at the end of the 60 minute charge.



Charge efficiency versus time for three charge voltages.

Figure 6

Figure 7 is a curve of cycles vs. discharge time in minutes for the three charge voltages. Also, a set of reference cells was charged at 2.5V constant-voltage for 16 hours and discharged at the 1C rate. This reference curve is displayed to show the expected capacity at the 1C rate. It can be seen from these curves that the 2.55V per cell curve most closely approximates the reference line. The cell charged at 2.7V per cell received too much overcharge and, therefore, the degradation in capacity after 15 cycles. The cell charged at 2.35V achieved a value of approximately 75% of the reference and continued to cycle at that level.

These tests show that the Gates sealed lead-acid cell can be fast-charged to 100% of rated capacity in less than one hour. A constant-voltage charger set at 2.5 to 2.55V per cell and capable of the 3C to 4C rate of charge is preferred.

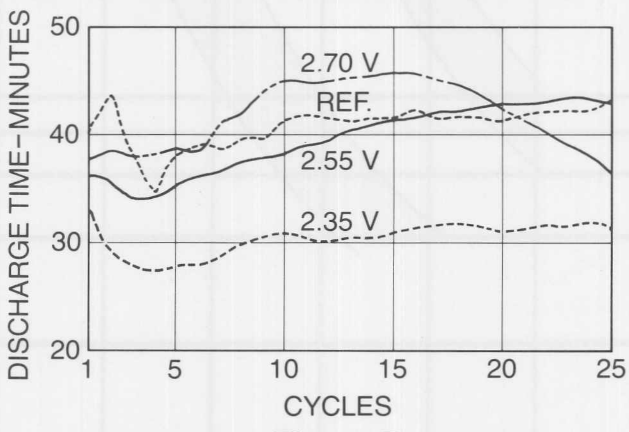


Figure 7

Float Charging

When the Gates sealed lead-acid cell is to be float-charged in a standby application, the constant-voltage charger should be maintained between 2.3 and 2.4V for maximum float life. Continuous charging at greater than 2.4V per cell is not recommended because of accelerated grid corrosion.

Figure 8 is a pair of curves of log overcharge rate vs. voltage for 25° C and 65° C. These curves give the approximate values of overcharge rate (charge current) that a cell will accept when float-charged at 25° C and 65° C. The cell must have been charged for a long enough period of time so that it is in a state of overcharge equilibrium before these curves can be considered accurate. These curves are also sufficient to determine what approximate value of continuous constant current (trickle charge) will maintain the proper float voltage. As an example, if a cell were trickle charged at the .001C rate, its average voltage on overcharge would be 2.35V. Conversely, if a cell were constant-voltage charged at 2.35V, its overcharge rate would be 0.001C.

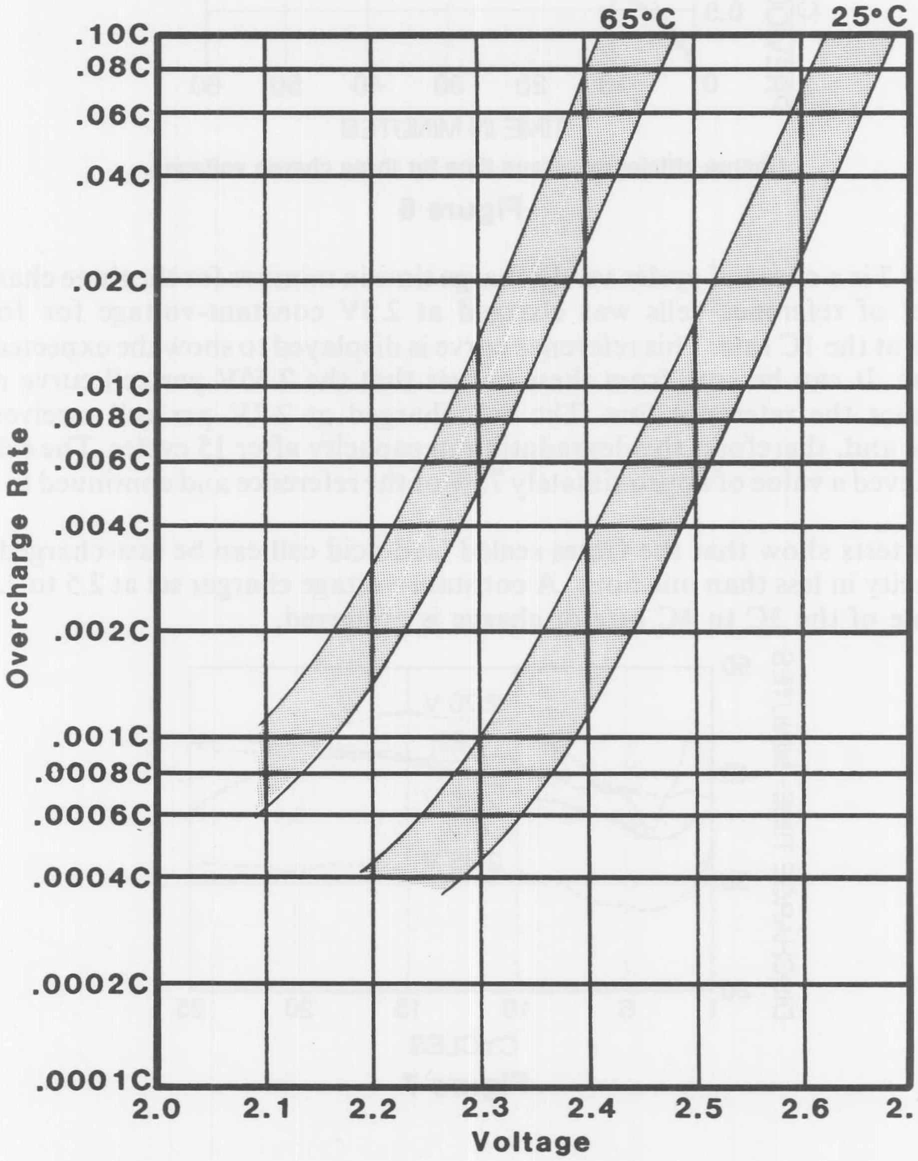


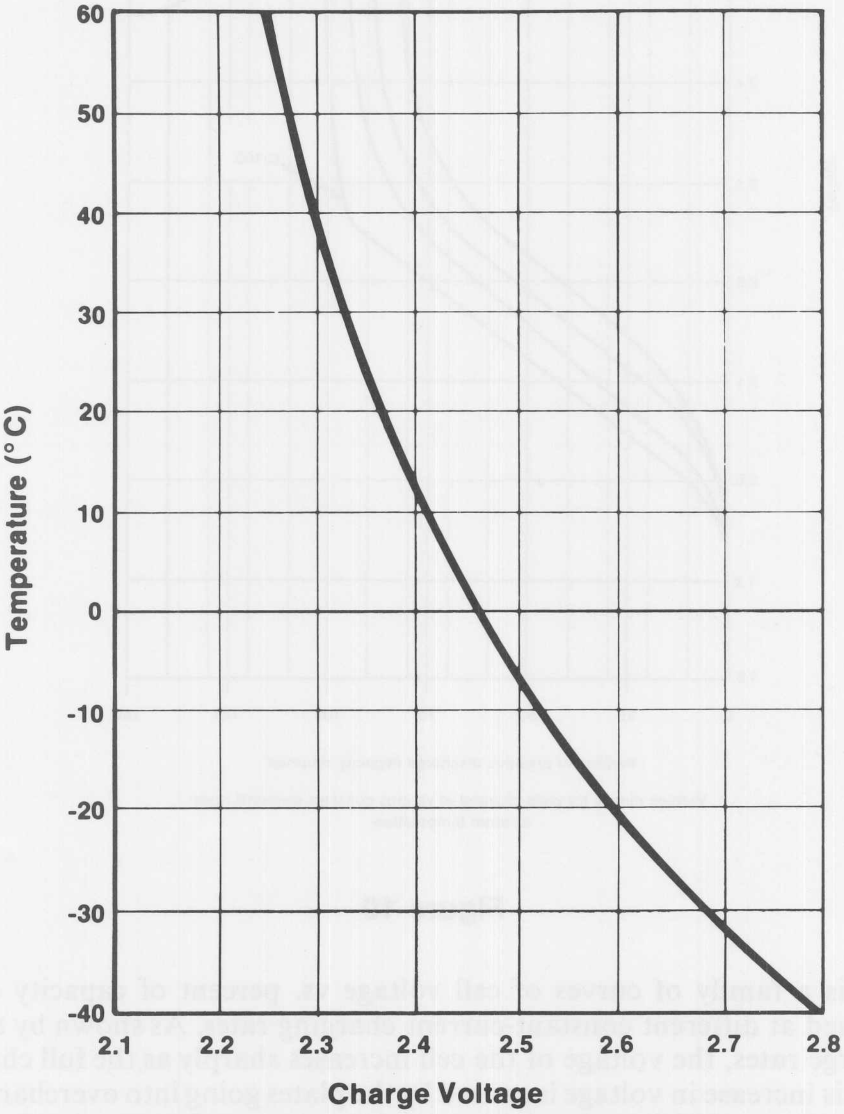
Figure 8

Temperature Compensation

High temperatures accelerate the rate of the reactions which reduce the life of a cell. At increased temperatures, the voltage necessary for returning full capacity to a cell in a given time is reduced because of the increased reaction rates within the battery. To maximize life, a negative charging temperature coefficient of approximately -2.5mv per °C per cell is used at temperatures significantly different from 25° C.

Figure 9 is a curve of charge voltage per cell vs. temperature showing the recommended charging temperature coefficient for a Gates cell float charged at 2.35V at 25° C. It is obvious from this curve that at extremely low temperatures, a significantly greater temperature coefficient than -2.5mv per °C is required to achieve full recharge of the cell.

When trickle charging, it may be necessary to increase the charge rate at higher temperatures to maintain the proper float voltage. From Figure 8, it can be shown that if a cell were trickle charged at the 0.001C rate at 25° C, then the float voltage would be 2.35. However, at the same rate at 65° C, the cell float voltage would be approximately 2.12, which is below the open circuit voltage of the cell. At 65° C, the trickle charge current would need to be increased to approximately 0.01C to maintain the proper cell float voltage.

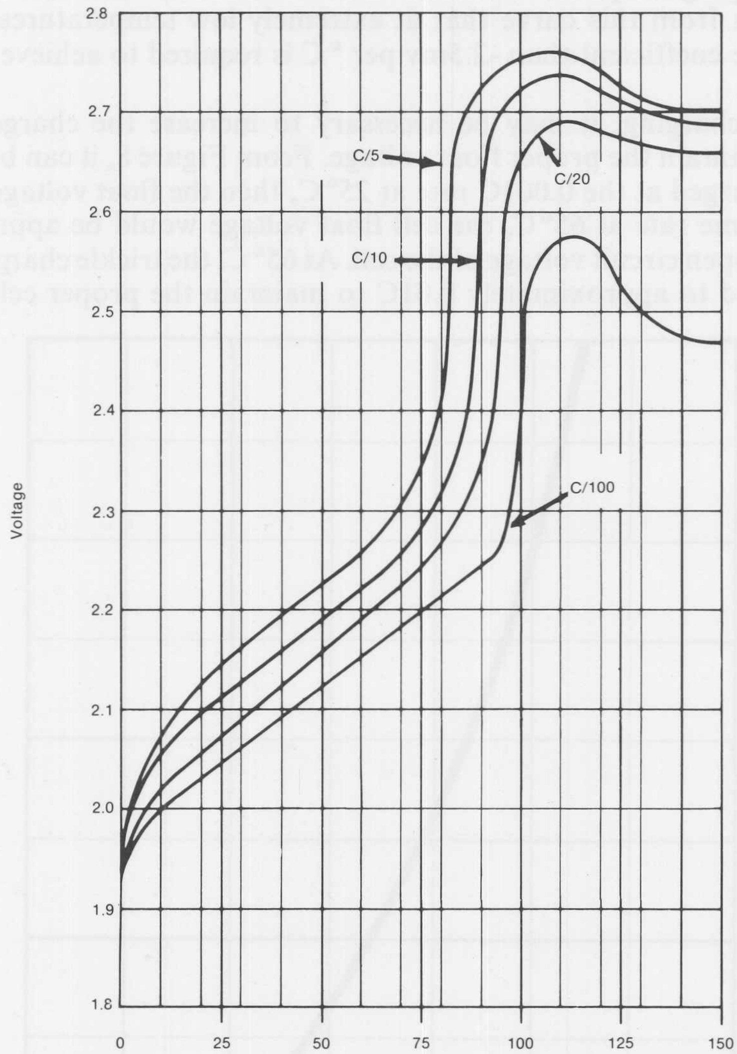


Recommended Temperature Compensation

Figure 9

Constant-Current Charging

Constant-current is another efficient method of charging the Gates cell. Constant-current charging of a cell or battery is accomplished by the application of a nonvarying constant-current source. This charge method is especially effective when several cells are charged in series since it tends to eliminate any charge imbalance in a battery. Constant-current charging charges all cells equally because it is independent of the charging voltage of each cell in the battery.



Percent of previous discharge capacity returned.

Voltage curves for cells charged at various constant (current) rates at room temperature.

Figure 10

Figure 10 is a family of curves of cell voltage vs. percent of capacity of previous discharge returned at different constant-current charging rates. As shown by these curves at different charge rates, the voltage of the cell increases sharply as the full charge state is approached. This increase in voltage is caused by the plates going into overcharge when the majority of the active material on the plates has been converted from lead sulfate to lead on the negative plate and lead dioxide on the positive plate. The voltage increase will occur at lower states of charge when the cell is being charged at higher rates. This is because at the

higher constant-current charge rates the charging efficiency is reduced. The voltage curves in Figure 10 are somewhat different than those for a conventional lead-acid cell due to the effect of the recombination of gases on overcharge within the system. The Gates cell is capable of recombining the oxygen produced on overcharge up to the C/3 rate of constant-current charge. At higher rates, the recombination reaction is unable to continue at the same rate as the gas generation.

While constant-current charging is an efficient method of charging, continued application at rates above C/500, after the cell is fully charged, can be detrimental to the life of the cell. At overnight charge rates (C/10 to C/20), the large increase in voltage at the nearly fully-charged state is a useful indicator for terminating or reducing the rates for a constant-current charger. If the rate is reduced to C/500, the cell can be left connected continuously and give 8 to 10 years' life at 25° C.

Figure 11 is a curve of voltage vs. time for a cell charging at the C/15 rate of constant current at 25° C. This cell had previously been discharged to 100% depth of discharge at the C/5 rate. This curve shows that the cell is not fully charged at the time the voltage increase occurs and must receive additional charging. If a Gates cell is to be charged with constant-current at higher than room temperature, then some temperature compensation must be built into the voltage-sensing network. As explained under Float Charging and Temperature Compensation, at higher temperatures and given charging rates, the cell voltage on overcharge is reduced. Therefore, the rise in voltage at close to full charge (Figures 10 & 11) will be somewhat depressed.

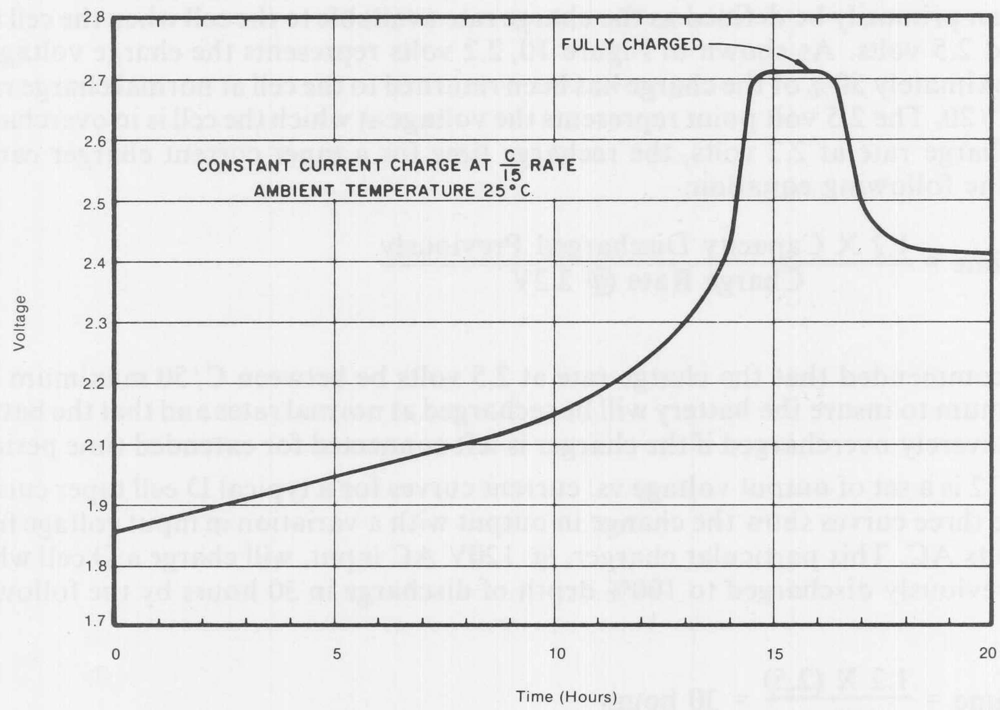


Figure 11

Taper Current Charging

Although taper current chargers are among the least expensive types of chargers, their lack of voltage regulation can be detrimental to the cycle life of any type of cell. The Gates cell has superior ability to withstand charge voltage variations, but some caution in using taper current chargers is recommended.

A taper current charger contains a transformer for voltage reduction and a half- or full-wave rectifier for converting from AC to DC. The output characteristics are such that as the voltage of the battery increases during charge, the charging current decreases. This effect is achieved by the proper wire size and the turns ratio. Basically, the turns ratio from primary to secondary determines the output voltage at no load, and the wire size in the secondary determines the current at a given voltage. The transformer is essentially a constant-voltage transformer which depends entirely on the AC line voltage regulation for its output voltage regulation. Because of this method of voltage regulation, any changes in input line voltage directly affect the output of the charger. Depending on the charger design, the output-to-input voltage change can be more than a direct ratio, e.g., a 10% line voltage change can produce a 13% output voltage change.

When considering the cost advantage of using a half-wave rectifier vs. a full-wave rectifier in a taper current charger, remember that the half-wave rectifier supplies a 50% higher peak to average voltage ratio than the full-wave rectifier. Therefore, the total service life of the battery for a given average charge voltage can be reduced for the half-wave type of charger because of the higher peak voltages.

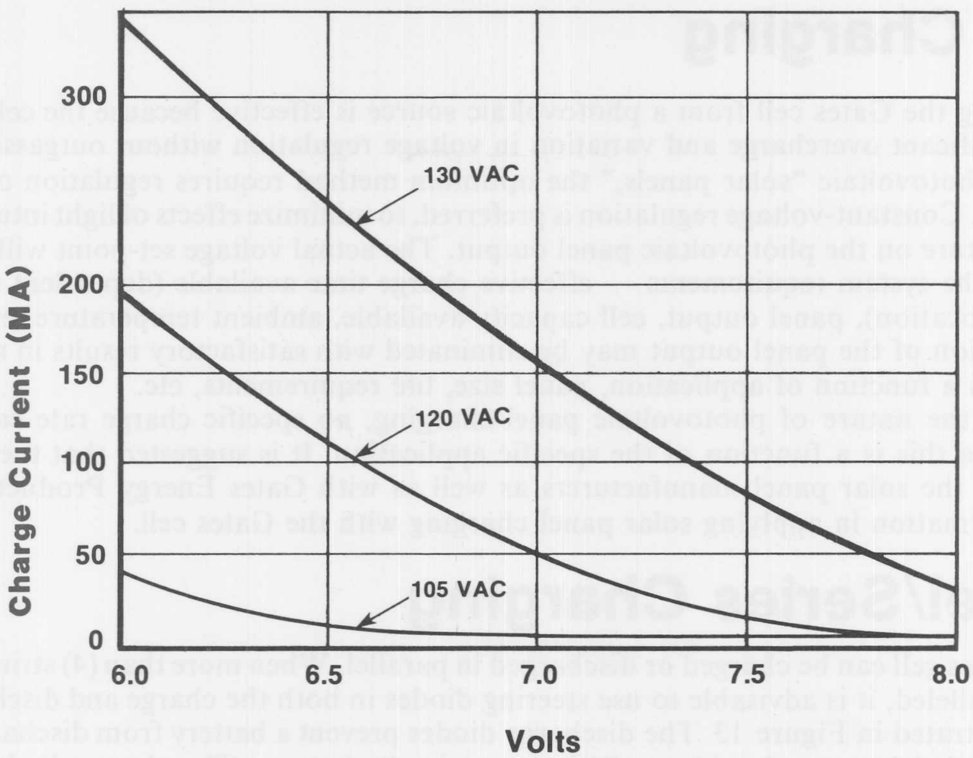
There are several charging parameters which must be met. The parameter of main concern is the recharge time to 100% nominal capacity for cycling applications. This parameter can primarily be defined as the charge rate available to the cell when the cell is at 2.2 volts and 2.5 volts. As shown in Figure 10, 2.2 volts represents the charge voltage at which approximately 50% of the charge has been returned to the cell at normal charge rates of C/10 to C/20. The 2.5 volt point represents the voltage at which the cell is in overcharge. Given the charge rate at 2.2 volts, the recharge time for a taper current charger can be defined by the following equation:

$$\text{Recharge Time} = \frac{1.2 \text{ X Capacity Discharged Previously}}{\text{Charge Rate @ 2.2V}}$$

It is recommended that the charge rate at 2.5 volts be between C/50 maximum and C/100 minimum to insure the battery will be recharged at normal rates and that the battery will not be severely overcharged if the charger is left connected for extended time periods.

Figure 12 is a set of output voltage vs. current curves for a typical D cell taper current charger. The three curves show the change in output with a variation in input voltage from 105 - 130 volts AC. This particular charger, @ 120V AC input, will charge a D cell which had been previously discharged to 100% depth of discharge in 30 hours by the following equation:

$$\text{Recharge Time} = \frac{1.2 \text{ X } (2.5)}{.100 \text{ A}} = 30 \text{ hours}$$



Taper Current Charger Characteristics

Figure 12

Vehicle Charging

The ability of the Gates cell to accept a high initial current with a constant-voltage charger allows the cell to be charged from an automobile alternator/regulator charging system, with some restrictions.

For example, a 12-volt battery may be connected to the vehicle charging system directly through the cigarette lighter plug. No additional circuitry is required to regulate the charge rate into the Gates battery, although the following restrictions apply:

1. The 12-volt Gates battery will charge only when the vehicle engine is running and the alternator/regulator functioning.

2. The Gates battery should not be connected when the vehicle engine is started. If connected, the battery will discharge with the vehicle battery during starting.

3. Minimum voltage output of the vehicle's regulator must be 13.8 volts. **Note:** a charge voltage less than 13.8 volts will not recharge the 12-volt Gates battery.

Dependent upon the value of the voltage output, the Gates battery may have 80% of its charge returned within 1-4 hours.

For charging other than 12-volt batteries, additional circuitry is required to regulate the charge rate and voltage. This circuitry should yield either a constant-current or constant-voltage output, per the charge recommendations outlined previously in this section.

Solar Charging

Charging the Gates cell from a photovoltaic source is effective because the cell can tolerate significant overcharge and variation in voltage regulation without outgassing.

Using photovoltaic "solar panels," the optimum method requires regulation of the panel output. Constant-voltage regulation is preferred, to minimize effects of light intensity and temperature on the photovoltaic panel output. The actual voltage set-point will be a function of the system requirements — effective charge time available (dependent upon geographic location), panel output, cell capacity available, ambient temperature, etc.

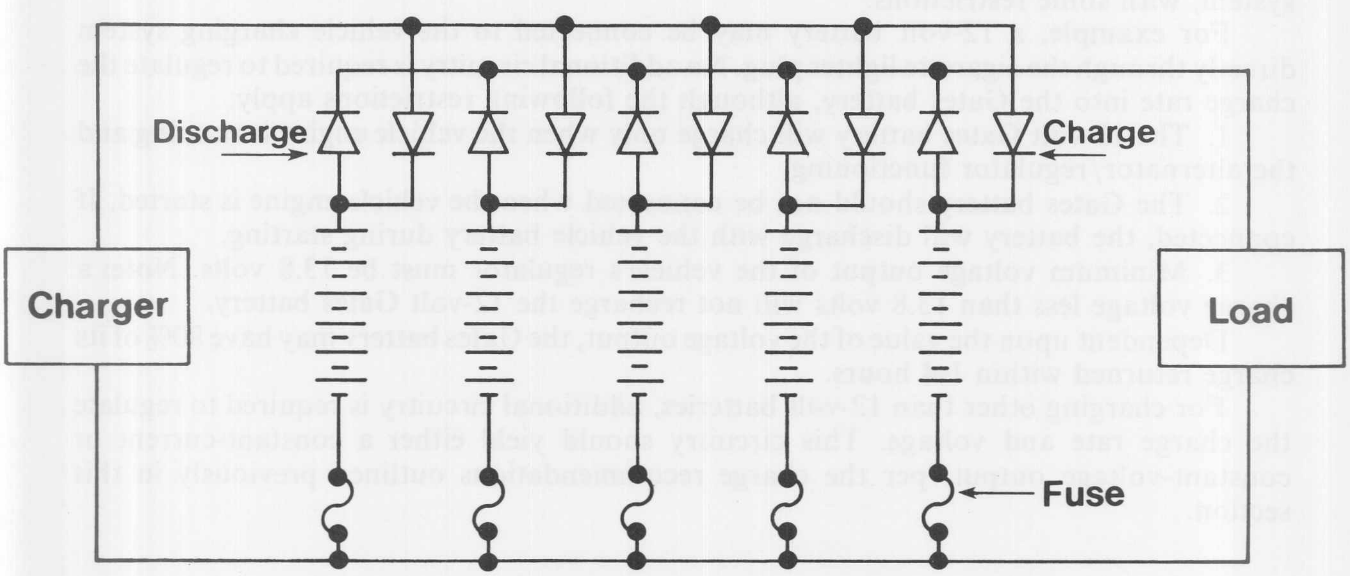
Regulation of the panel output may be eliminated with satisfactory results in many cases. This is a function of application, panel size, life requirements, etc.

Due to the nature of photovoltaic panel charging, no specific charge rate can be defined, since this is a function of the specific application. It is suggested that the user consult with the solar panel manufacturers as well as with Gates Energy Products for specific information in applying solar panel charging with the Gates cell.

Parallel/Series Charging

The Gates cell can be charged or discharged in parallel. When more than (4) strings of cells are paralleled, it is advisable to use steering diodes in both the charge and discharge path, as illustrated in Figure 13 The discharge diodes prevent a battery from discharging into a paralleled battery should a cell short out in the battery. The charge diodes, in conjunction with the fuse, will prevent a battery with a shorted cell from accepting all the charge current from the charger and subsequently prevent the other paralleled batteries being fully charged. The fuse should be sized by dividing the maximum charge current by the number of batteries in parallel and multiply this value times two. This should result in the fuse opening on charge in a parallel string which has a shorted cell.

When float-charging many cells in series, (12) or more for example, it is advantageous to use a trickle charge of c/500 maximum in parallel with the float charger. Some examples of this are explained in the charger section (8). This trickle charge will tend to balance all cells in the battery by driving a continuous trickle charge through all cells equally.



Parallel Operation

Figure 13

Charge Current Efficiency

Charge current efficiency is the ratio of current which is actually used for electrochemical conversion of the active materials from lead sulfate to lead and lead dioxide vs. the total current supplied to the cell on recharge. The current which is not used for charging is consumed in parasitic reactions within the cell such as self-discharge, gas production, etc.

The charging efficiency is excellent for a Gates cell. The distinctly high ratio of plate surface area to ampere-hour capacity allows for higher charging rates and, therefore, efficient charging.

Charge current efficiency is a direct function of state of charge. In all the following curves the charge current efficiency is calculated to full 100% recharge. Obviously, past the point of full recharge, the efficiency falls to zero.

Figure 14 is a curve of state of charge vs. charge current efficiency for a cell charging at the C/20 rate of constant current or a constant voltage of 2.4. As can be seen in this curve, the charge efficiency of a cell is high until it approaches full charge, at which time the overcharge reactions begin and the charge efficiency decreases.

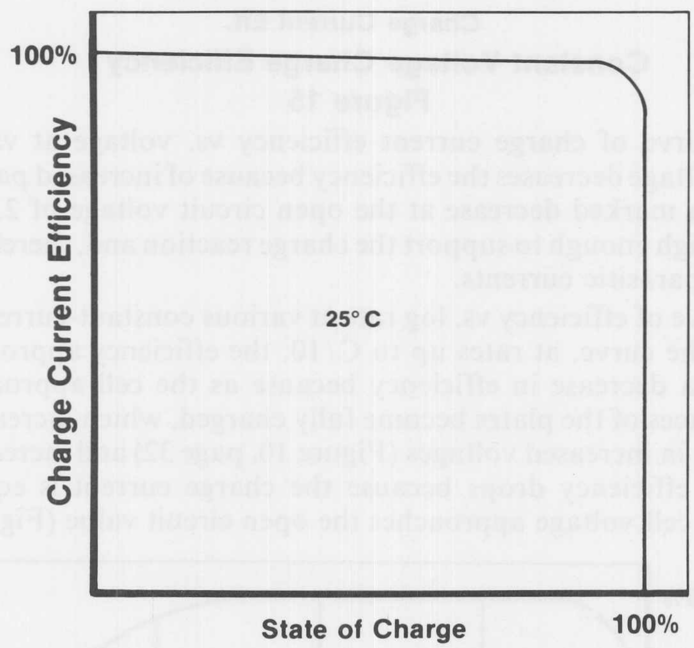
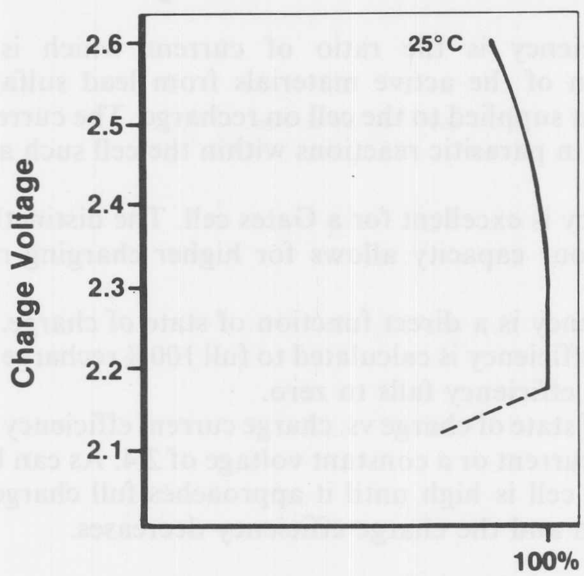


Figure 14



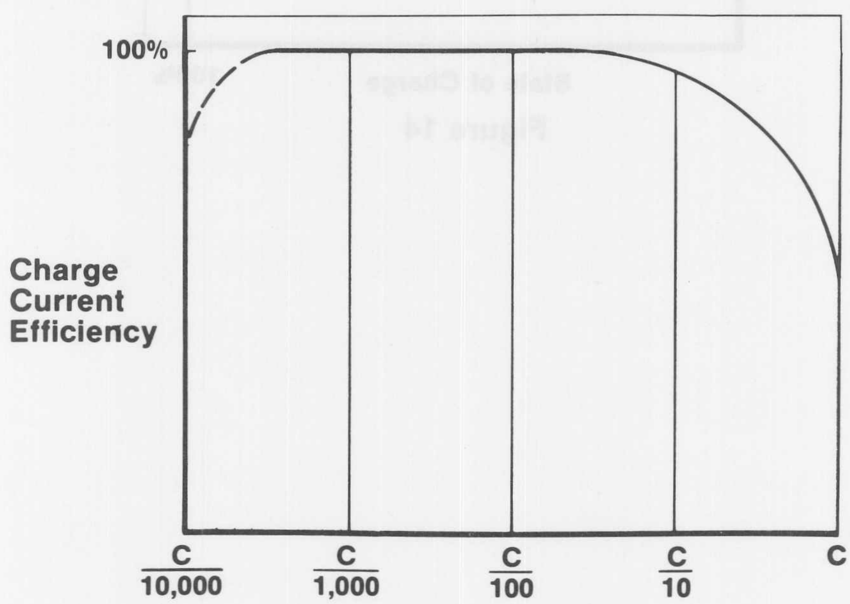
Charge Current Eff.

Constant Voltage Charge Efficiency

Figure 15

Figure 15 is a curve of charge current efficiency vs. voltage at various constant voltages. Increasing voltage decreases the efficiency because of increased parasitic currents. The efficiency shows a marked decrease at the open circuit voltage of 2.18, because the charge voltage is not high enough to support the charge reaction and, therefore, the current is only supplying the parasitic currents.

Figure 16. is a curve of efficiency vs. log rate at various constant-current charge rates. As can be seen from the curve, at rates up to C/10, the efficiency approaches 100%. At higher rates, there is a decrease in efficiency because as the cell approaches the fully-charged state, the surfaces of the plates become fully charged, which increase the charging reaction rates resulting in increased voltages (Figure 10, page 32) and increased gassing. At low charge rates, the efficiency drops because the charge current is equivalent to the parasitic currents and cell voltage approaches the open circuit value (Figure 8, page 30).



Charge Rate

Constant Current Charge Efficiency

Figure 16

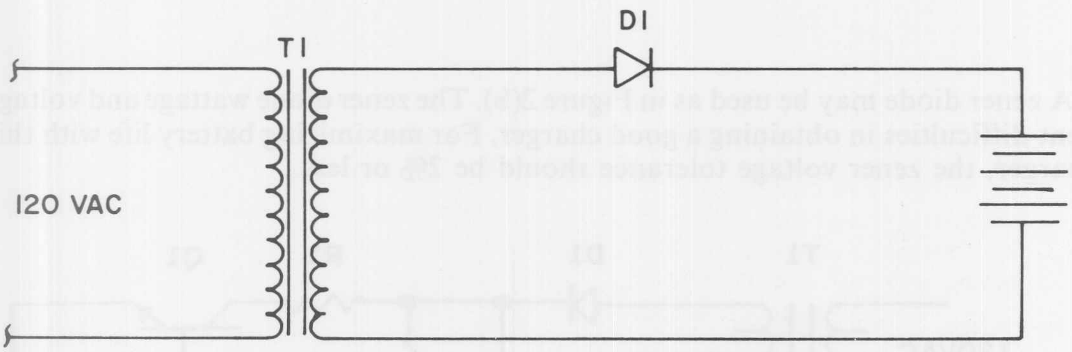
CHARGER CIRCUITS

Charging of batteries can be approached in many different ways, but the lead-acid system traditionally has been linked to constant-voltage charging. Constant current will charge a conventional lead-acid battery, but overcharge effects may be undesirable. The Gates cell will accept reasonable overcharge without damage, thus enlarging the number of charging schemes which can be used.

The application will usually define the charging system to be used. Factors such as cost, cyclic or float operation, depth of discharge, recharge time, battery service life, operating temperature range, available power sources and other requirements influence the selection of the charging system.

Constant Voltage

The constant-voltage charger may be no more than a low-impedance transformer with a rectifier, as shown in Figure 1, commonly called a taper-current charger. This type of construction has no line voltage regulation and will not give maximum battery service life (see page 34).



A simple constant voltage charger.

Figure 1

Figure 2(a) is an improvement on this type of charger. By adding three diodes to the output of a taper current charger, the charging voltage is controlled and can compensate for line voltage variations.

The circuit of Figure 2(a) can be made using three silicon diodes which have approximately 0.8 volts forward drop at 200 ma. This is assuming a transformer design which allows a current-voltage relationship compatible with the diodes.

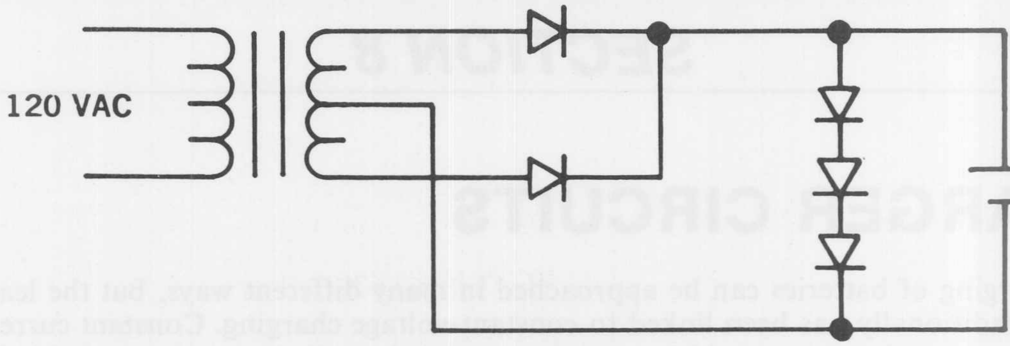
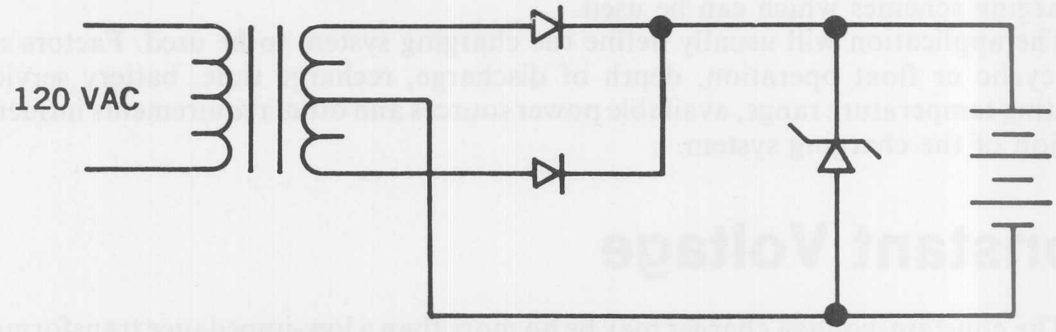


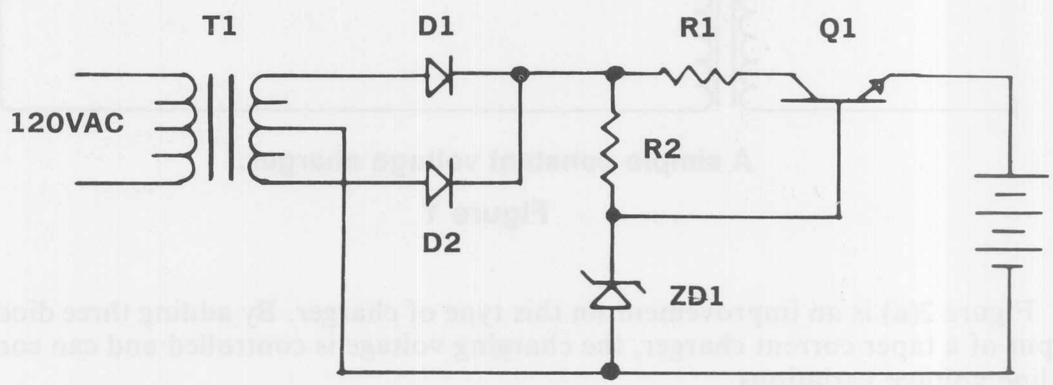
Figure 2(a)



Constant voltage charger 2 (a) a single cell charger 2 (b) a charger using a zener diode.

Figure 2(b)

A zener diode may be used as in Figure 2(b). The zener diode wattage and voltage may present difficulties in obtaining a good charger. For maximizing battery life with this type of charger, the zener voltage tolerance should be 2% or less.

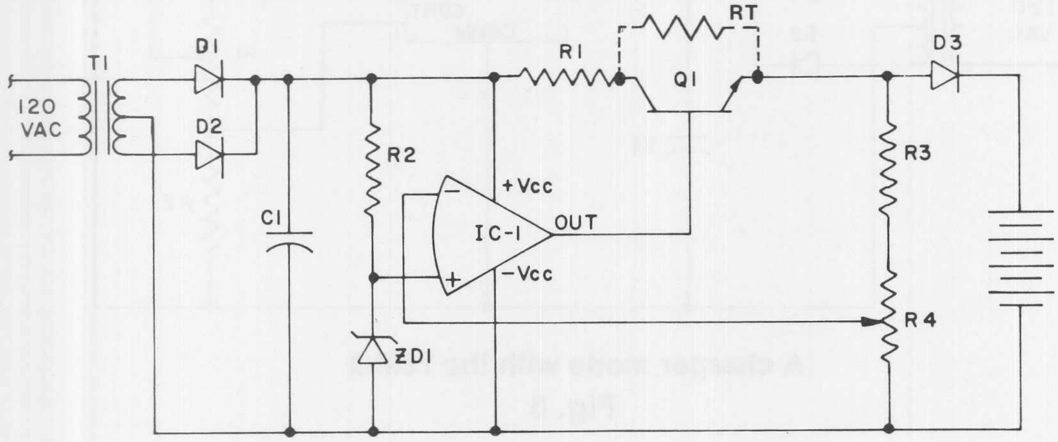


A constant voltage charger using a zener diode and a series-pass transistor.

Figure 3

The circuit of Figure 3 is a further improvement on the constant-voltage charger. The wattage of the zener will be reduced from that of Figure 2(b) but zener tolerance must be the same. The wattage required is reduced by the emitter follower operation of Q1. Resistor R1 is used to limit current and reduce dissipation in transistor Q1.

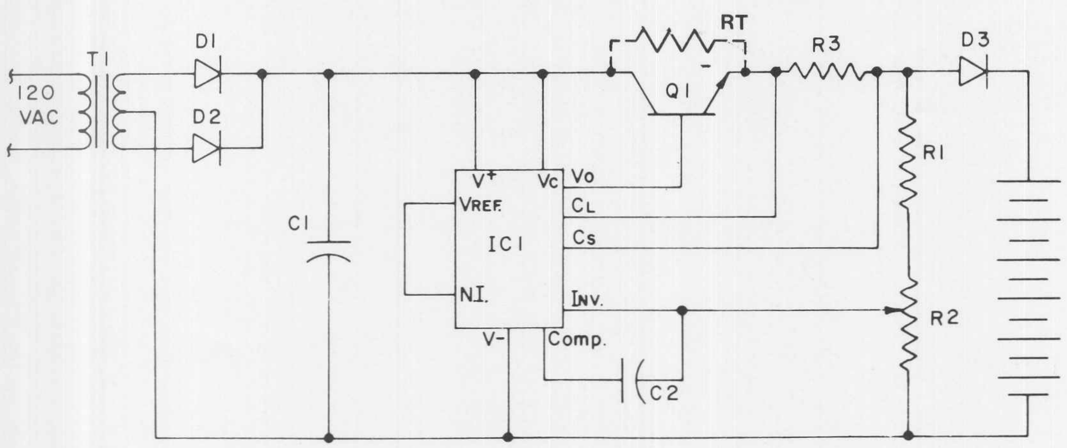
Many variations can be made using discrete components. A good source for such circuits and design methods may be found in literature concerning constant-voltage regulators and power supplies. Some precautions should be taken when using standard power supply circuits. First, be sure that the battery cannot discharge into the power supply circuitry. This will sometimes result in damage to the circuit as well as result in a discharged battery. Another problem commonly encountered is instability with the battery connected. This is similar to problems with highly capacitive loads and may be corrected by using the same technique. Power supply circuits may use current fold-back, instead of current limiting. Current limiting is preferred for obvious reasons.



A constant voltage charger using an operational amplifier.

Fig. 4

Integrated circuits have greatly increased the ease of designing constant-voltage chargers. The operational amplifier offers extremely high gain in a low cost package. The charger of Figure 4 is a simple charger using an op-amp to detect charging voltage and control the series pass transistor, accordingly. The output of this type of charger is better regulated than circuits previously described. The regulation of this circuit can be improved by moving the sense network R3, R4 to the cathode side of D3. This will allow a discharge path for the battery, but for most applications the discharge rate can be made very small.



μA723 used as a battery charger

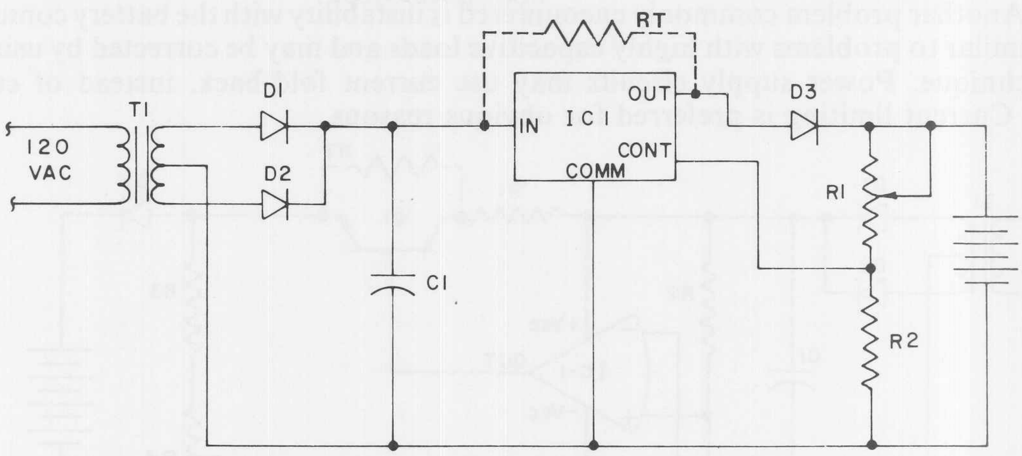
Fig. 5

Parts List for 12V "D"

C1 — 250 MFD 50WVDC
C2 — 500 pf 25V
D1, D2, D3 — 1N4001
Q1 — 2N3055
IC1 — uA723

R1 — 4.7K Ohm 1/2W 10%
R2 — 5K Ohm 1/2W 10%
R3 — 1 Ohm 1W 5%
T1 — 40V RMS CT @ 1A

Several manufacturers now offer voltage regulators in integrated form. Figure 5 is an example of a charger using the uA723 voltage regulator. This regulator offers high performance and low cost. The regulator is easily adapted to the desired output voltages by use of voltage dividers. A full description of the regulator may be found in literature offered by the various manufacturers (Fairchild, Signetics, Motorola, National, etc.).



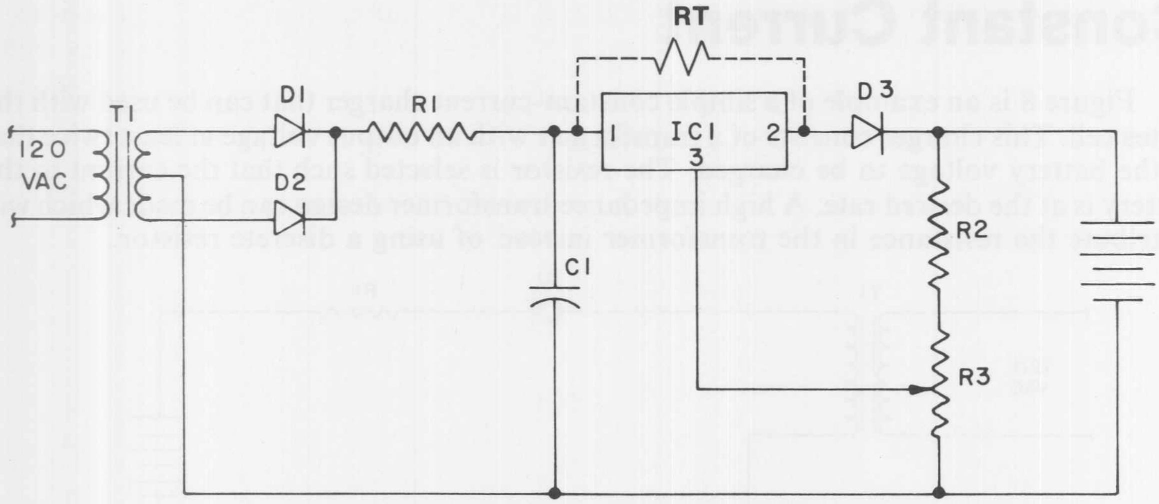
A charger made with the 78MG

Fig. 6

Parts List for 6V "D"

C1 — .33 MFD 50V
D1, D2, D3 — 1N4001
R1 — 25K Ohm 1/2W 10%
R2 — 5K Ohm 1/2W 10%
T1 — 16V RMS CT @ 0.35A
IC1 — 78MGT2C (Fairchild)

The 78MG voltage regulator offered by Fairchild is particularly easy to use and is relatively low-priced. Figure 6 shows a charger using the 78MG. The 78MG has a built-in 5-volt reference and a 500-ma transistor. The regulator is protected for most common problems, such as exceeding Safe Operating Area and overcurrent. The small size and ease of selecting output voltages makes this regulator a simple but highly effective charger.



A charger using a LM309

Figure 7

Parts List for 6V "D"

C1 — .22 MFG 50V
D1, D2, D3 — 1N4001
R1 — 3.75 Ohm, 12 Watt
R2 — 220 Ohm, 1/2 Watt
R3 — Trimpot, 1000 Ohm, 0.75 Watt Bourns Model 3006P (or equivalent)
T1 — Transformer, 26.8 VAC CT Triad Model F40X (or equivalent)
IC1 — Voltage Regulator, National Semiconductor Model LM309K (or equivalent)

Figure 7 is another example of a well-regulated constant-voltage battery charger. The voltage regulation device used in this charger is a 3-lead, fixed 5-volt regulator produced by National Semiconductor, Motorola, Fairchild, etc. This type of voltage regulator controls the voltage between lead 3 and lead 2 at exactly 5 volts. This regulator is also protected from overcurrent and Safe Operating Area problems.

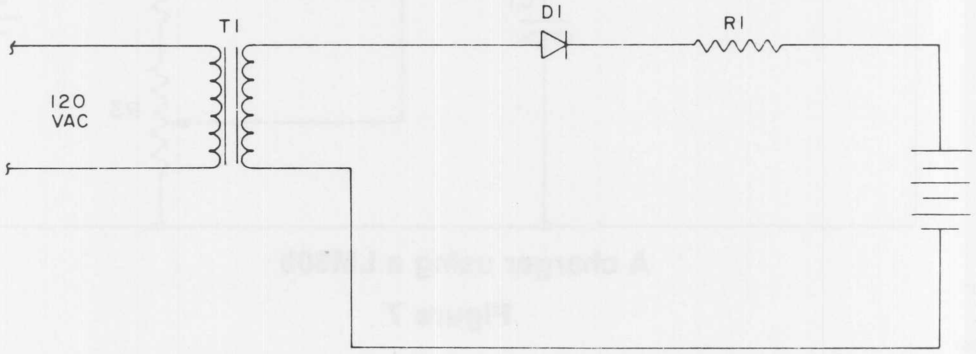
Resistor RT allows for a small trickle current of approximately 5 ma (C/500 rate) to charge the battery at all times. This trickle charge is recommended especially where a large number of cells is to be charged in series. The continuous trickle charge will balance all cells equally in a float charge application. The continuous trickle charge from a higher voltage source also serves to promote the recharge reaction in cells which have been deeply discharged.

One word of caution when using these integrated voltage regulators: do not allow the substrate to become forward biased. If this happens, the voltage regulator can be damaged. For example, assume diode D3 in Figure 7 is not present and the AC power is interrupted to the circuit, the battery would become a current source, and the regulator could be damaged. This can be prevented by using D3 as shown, or by placing D3 anode to Pin 2 and cathode to Pin 1. The diode connected in this manner will protect the regulator, but it may also discharge the battery. More information concerning this regulator may be found in the literature available from the manufacturers.

More elaborate chargers can be constructed using constant-voltage techniques. Some of these may incorporate two voltage levels with automatic switching from one level to another, dependent on the current levels. A charger using this technique could supply a fast charge by using a high voltage and then a reduced voltage when the current indicates a fully-charged state has been reached. The switch from high to low voltage may also be controlled by a timer.

Constant Current

Figure 8 is an example of a simple constant-current charger that can be used with the Gates cell. This charger consists of a transformer with an output voltage at least twice that of the battery voltage to be charged. The resistor is selected such that the current to the battery is at the desired rate. A high impedance transformer design can be made which will distribute the resistance in the transformer instead of using a discrete resistor.



A Simple Constant Current Charger.

Figure 8

A resistor may be used as shown in Figure 9 to create a constant-current charger directly from an AC or DC source. One problem with this type of constant-current charger is the large power rating required of the resistor and the resulting heat which must be dissipated.

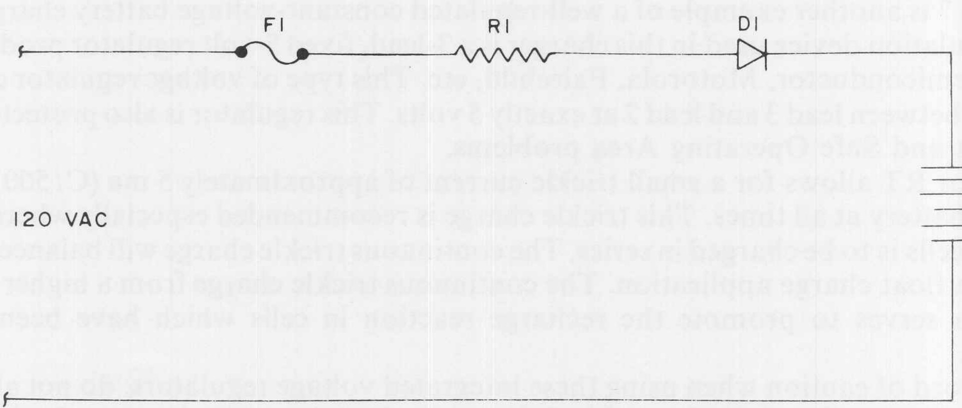
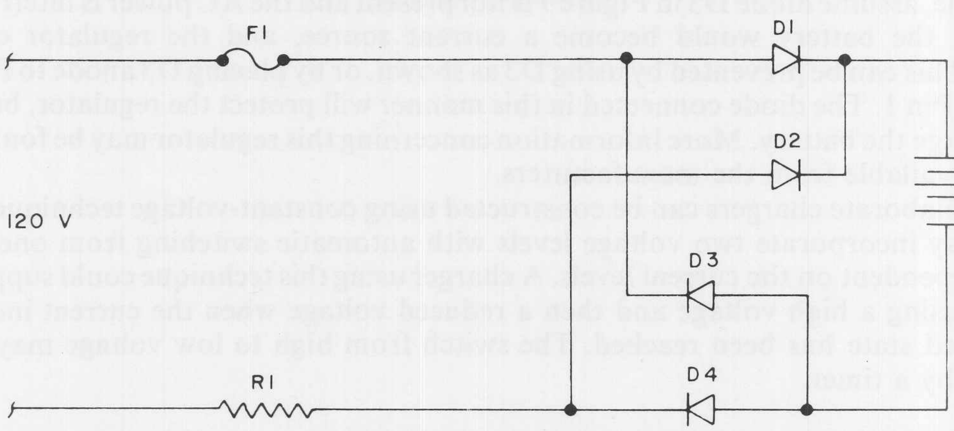


Figure 9(a)



Constant current chargers made with resistors 9 (a) half wave 9 (b) full wave.

Figure 9(b)

An alternate method to using a dissipative element is shown in Figure 10. In this type of circuit, a capacitor is used to supply the impedance for the charger. The capacitor has low dissipation and will reduce heat from the charger.

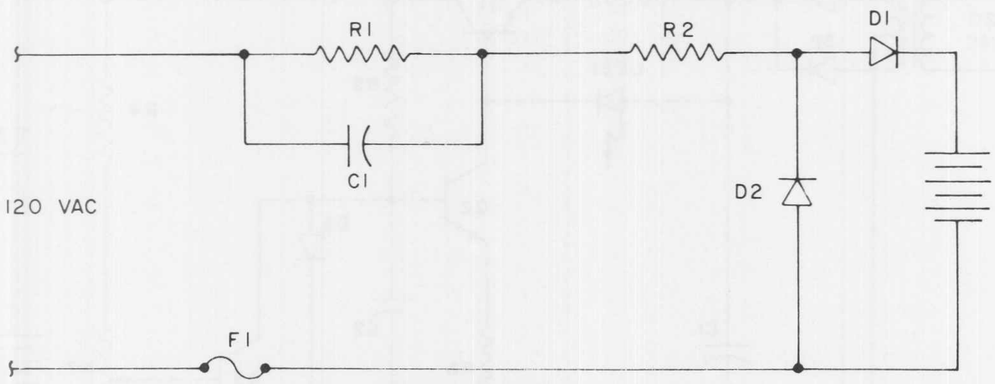
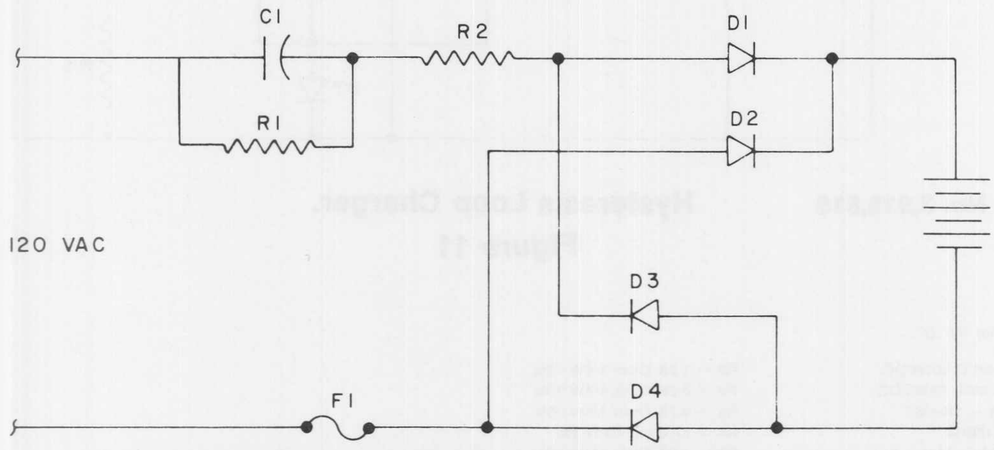


Figure 10(a)



Reactance Chargers 10 (a) Half Wave 10 (b) Full Wave.

Figure 10(b)

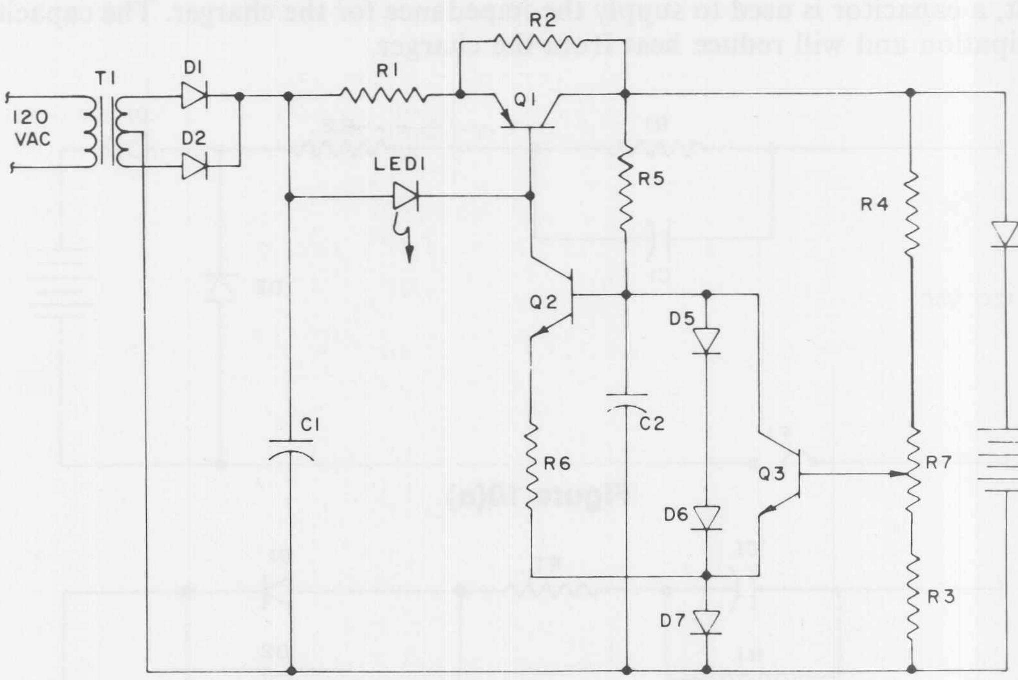
Extreme care should be exercised when using any line-operated charger such as those shown in Figures 9 and 10. They are simple and low cost but present electrical hazards and may be undesirable in some applications. Adequate insulation and fusing should always be used.

Two-Step Constant Current Chargers

Two-step chargers offer the most desirable characteristics for battery life and recharge performance.

The hysteresis loop charger of Figure 11 is a two-step constant current charger. This charger displays automatic turn-on if the battery voltage is low and automatic reduction of charge rate when the battery is approximately 90% charged. The hysteresis loop charger is a high-performance, low-cost charger with the following characteristics:

1. Sixteen hours recharge to 95%.
2. Can be left connected without overcharge.
3. Output short circuit protected.
4. Automatic start-up in high rate.
5. Easily adapted to various voltage and ampere hour rating.
6. Small physical size.
7. High-rate indicator.



Patent No. 3,919,618 **Hysteresis Loop Charger.**

Figure 11

Parts List for 6V "D"

C1 — 250 MFD 50WVDC	R3 — 1.2K Ohm 1/4W 10%
C2 — .005 MFD 25WVDC	R4 — 8.2K Ohm 1/4W 10%
D1, D2, D8 — 1N4001	R5 — 4.7K Ohm 1/4W 10%
D5, D6 — 1N914	R6 — 27 Ohm 1/4W 5%
D7 — MZ2360 (Motorola)	R7 — 1.0K Ohm 1/4W 20%
LED-1 — FLV117	Q1 — D41D1 (GE)
R1 — 5.1 Ohm 1/2W 5%	Q2, Q3 2N3567
R2 — 390 Ohm 1/2W 5%	T1 — 20V RMS CT @ 0.3A

In Figure 11, the combination of resistor R1, LED-1, and transistor Q1 forms a constant-current source. This constant-current source determines the high rate current for the charger. Resistor R2 with resistor R1 form a path for current in the trickle charge mode.

Assuming the charger is in low rate, the resistive divider network consisting of R3, R4, and R7 is used to supply the correct voltage to the base of Q3 so that Q3 is in or near saturation. With Q3 saturated, the current through D7 is essentially supplied by resistor R5. This current will be relatively low, and the forward voltage drop of D7 will be low. Transistor Q2 will be in cutoff so the current source (Q1) will be disabled and allow only a trickle rate of charge to flow through R2.

As the voltage of the cell is reduced, the voltage on the divider network R3, R4, and R7 will be reduced. When the voltage at the base of Q3 is no longer high enough to hold Q3 in saturation, current will begin to flow to the base of Q2, turning Q2 on. With Q2 on, the current through D7 is high and the forward voltage drop of diode D7 is increased. The increase in voltage drop across D7 insures that transistor Q3 is in cutoff. The turn-on of Q2 enables the current source (Q1), and the charger is in the high-rate charging mode.

The charger will continue in high-rate until the voltage at the base of Q3 is sufficient to saturate Q3 and turn off Q2.

Capacitor C1 serves as a filter and capacitor C2 as a bypass. Diode D8 protects the battery from discharging into the charger when the input voltage to the charger is low or not present.

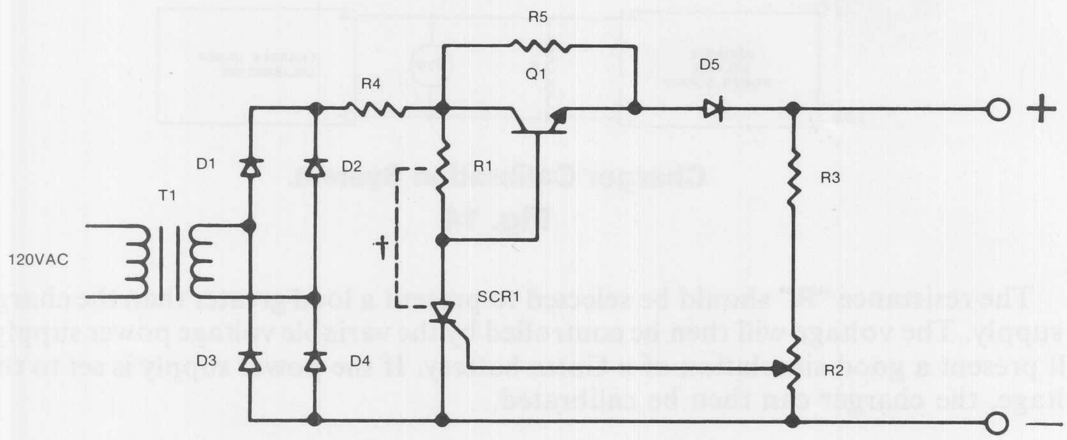
Desirable set points and currents for the hysteresis charger are determined by the intended usage. For a five-day per week cycling application, good performance can be obtained by using a loop of approximately 150 millivolts per cell. For example, a 6-volt "D" battery would be charged properly for a cycling application by using a high-to-low current set point of 7.5 volts and low-to-high current set point of 7.05 volts. High-rate current for a "D" battery should be near 160 milliamperes with the low-rate current about 20 milliamperes. These voltage and current relationships are recommended only for cycling operations.

For float applications, recommended set points are 7.35 volts and 6.9 volts respectively. The low-rate current also should be reduced to 5 milliamperes by changing R2 to a 1.0 kΩ ½ W resistor.

The hysteresis loop charger can be adapted to various ampere hour batteries by changing resistors R1 and R2. To change battery voltages, resistors R5 and R3 will require adjustments.

Another two-step constant-current charger is shown in Figure 12. This charger will charge the cell at constant current until the voltage on the battery rises to a predetermined set point of approximately 2.57 volts per cell, at which time the charge termination is begun and the charger switches to a low maintenance trickle charge level. Resistor R4 is a current limiting resistor which determines the output current of the charger. Resistor R5 is the bypass resistor that determines the trickle maintenance current level once the charger has terminated charge. Resistor R1 biases transistor Q1 full-on which produces the constant-current charge. During the initial charge, SCR1 remains ungated due to the value set between the wiper of resistor R2 and the negative buss of the charger. When the battery is 80-90% charged, the battery voltage begins to rise significantly.

As the voltage rises to the set point of 2.57 volts per cell, SCR1 begins firing during extremely small portions of the full wave cycle. R1 and SCR1 are thermally-connected, and as SCR1 starts conducting, a mutually-regenerative heating occurs. As the SCR gets hotter, it is gated full-on, which biases transistor Q1 full-off and the charger has switched to the trickle charge rate.

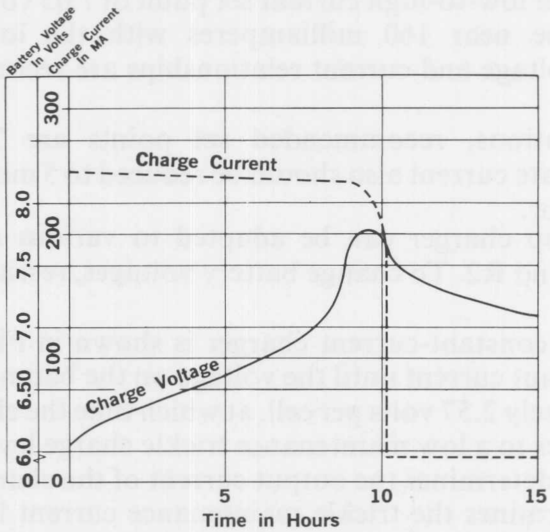


Parts List for 6V "D"

D1, D2, D39, D4, D5 — 1N4001
Q1 — 2N3567
R1 — 100 Ohm, 1 Watt, 10%
R2 — Trimpot, 250 Ohm, 1/4 Watt, IRC Model X-201
R3 — 2000 Ohm, 1/2 Watt, 5%
R4 — 15 Ohm, 2 Watt, 10%
R5 — 330 Ohm, 1/2 Watt, 5%
SCR1 — G. E. Type C107F1X2
T1 — Transformer, 10VAC 500 MA
†R1 and SCR1 are thermally connected

Shunt SCR Charger.
Fig. 12

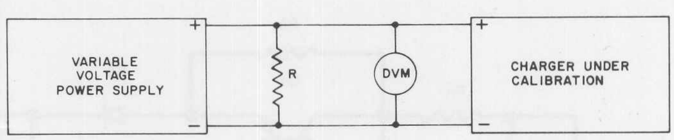
Figure 13 is a set of curves of the charge current and charge voltage for the shunt SCR charger. As can be seen from Figure 13, the charger does not immediately switch off when the set point is reached, but has a built-in thermal time lag which results in obtaining a full 100% capacity recharge before it switches to the trickle rate. This charger is set by connecting it to a partially-charged battery pack and observing on an oscilloscope the point at which SCR1 starts conducting. The charger must be at thermal equilibrium before R2 is then adjusted so that SCR1 begins firing when the battery voltage is at 2.57 volts per cell.



Charging Characteristics of Shunt SCR Charger.
Fig. 13

Battery Charger Calibration

Many chargers require calibration. Due to the unusual voltage current relationship of a battery, a battery simulator should be used. Figure 14 is an example of a battery simulator.



Charger Calibration System.
Fig. 14

The resistance "R" should be selected to present a load greater than the charger is able to supply. The voltage will then be controlled by the variable voltage power supply and this will present a good simulation of a Gates battery. If the power supply is set to the correct voltage, the charger can then be calibrated.

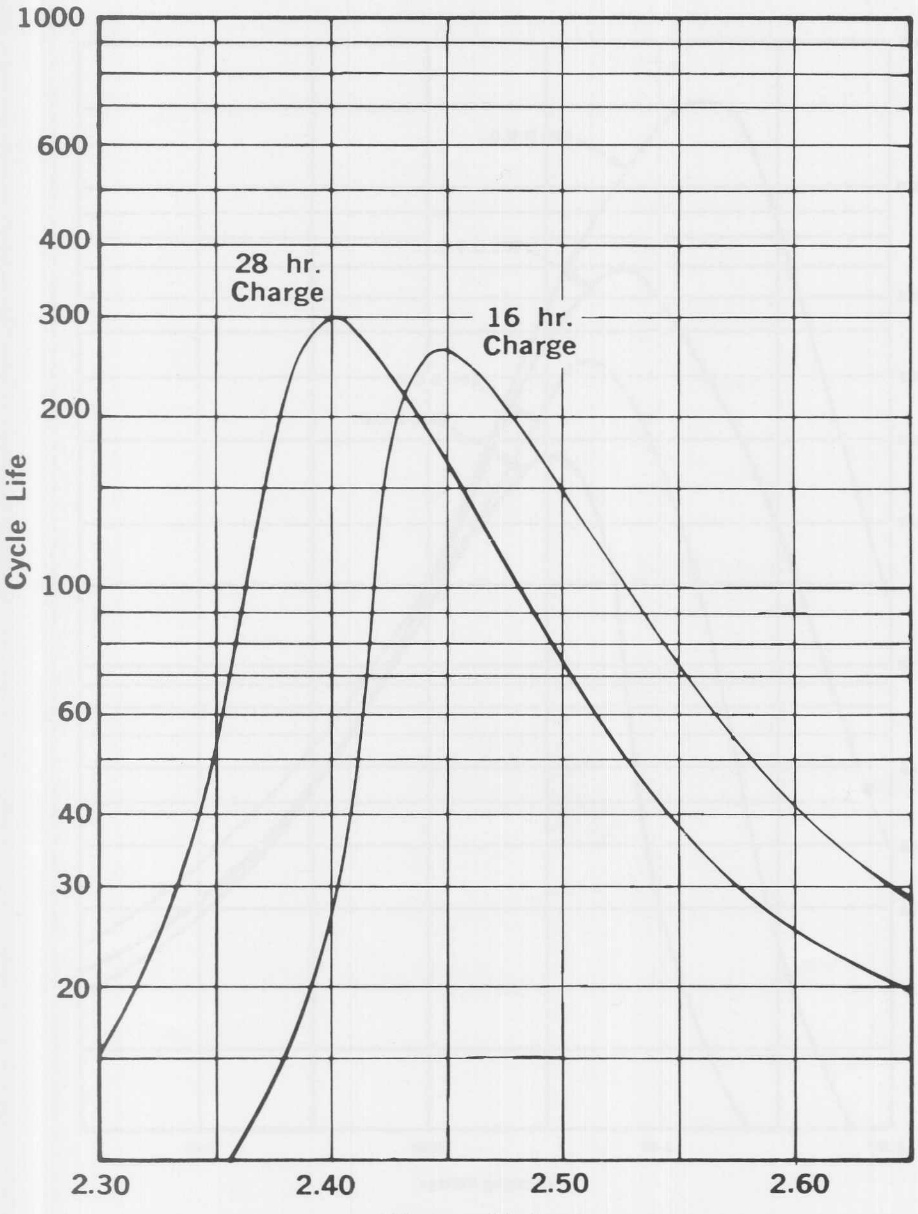
For specific charging applications, please contact Gates Energy Products, Inc.

SECTION 9

SERVICE LIFE

All battery systems have extremely variable service life, depending upon the type of cycle, environment, and charge to which the cell is subjected during its life. The Gates cell is no exception to this rule. There are two basic types of service life: cycle and calendar life.

Cycle Life

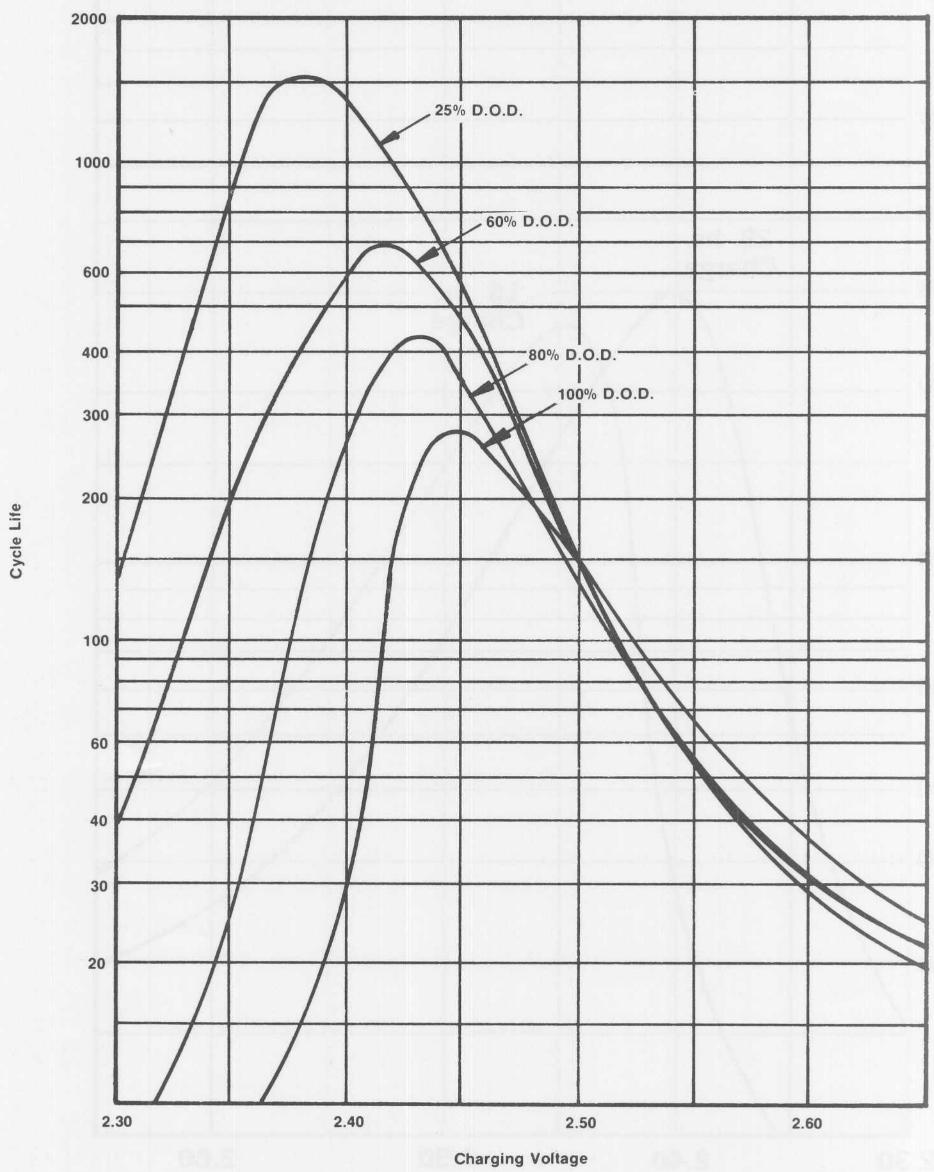


Effect of Charge Voltage on Cycle life at various charge times at 23°C, (73°F) (approx. 100% Depth of Discharge).

Figure 1

Figures 1 and 2 demonstrate the effect of three of the principle factors which control cycle life. The discharge rate was C/5 to an end of discharge of 1.6 volts. The end of cycle life in Figure 1 was defined as failure to achieve 80% of rated capacity at that rate. This figure demonstrates the need to select the proper charging voltage for a particular cycle regime. Figure 1 is somewhat misleading, however, in that it would indicate that a low-charging voltage, say 2.35, would yield a low cycle life and this is not true. For example, for an application where the cells would be used about three times a week and left on charge the rest of the time, then 2.35 volts would be quite adequate. Most of the capacity can be returned to the cells within 16 hours as was discussed in Charging Section 7. The occasional long charge periods would maintain capacity and thus optimize the total cycle life. Generally, 2.45 volts per cell is a better charging voltage for regimes of about one cycle per day.

Figure 2 shows the general effect of depth of discharge on cycle life. It demonstrates that high cycle life can be achieved by slight oversizing of the battery for the application.



Effect of Depth of Discharge on Cycle Life as a Function of Charging Voltage, 23°C, (73°F), 16 hour charge.

Figure 2

Figure 3 represents the average capacity of the Gates "D" cell as a function of cycle life at one cycle per day at a depth of discharge in excess of 90%. The standard deviation of the individual cell capacities from this average capacity is shown at 100 cycles.

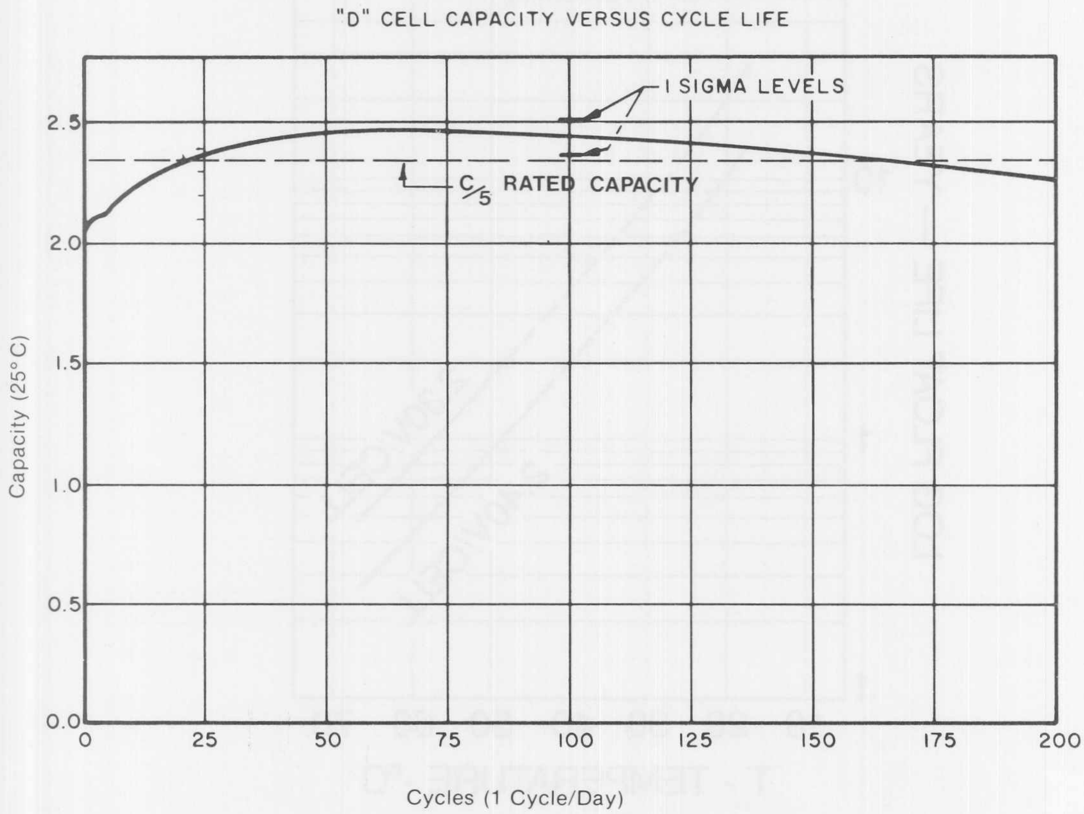


Figure 3

Float Life

Expected float life of the Gates cell is greater than eight years at room temperature. The expected float life was arrived at by using accelerated testing methods, specifically by the use of high temperatures.

The most widely-accepted accelerated test methods were summarized by E. Willihnganz in "Electrochemical Technology," September/October 1968 — "Accelerated Life Testing of Stationary Batteries." Gates Energy Products tests conform to these testing procedures. The primary failure mode of the Gates sealed lead-acid cell can be defined as growth of the positive plate. Because this growth is the result of chemical reactions within the cell, the rate of growth increases with increasing temperature as expressed by the widely-accepted Arrhenius equation.

Figure 4 is a curve of log float life vs. temperature (in degrees Celsius). The solid lines represent data from float life tests performed at two float voltages, 2.3V and 2.4V per cell. The lines have been extended through lower temperatures in accordance with the Arrhenius equation. This graph can be used to determine the expected float life at various temperatures. End of life is defined as the failure of the cell to deliver 80% of rated capacity.

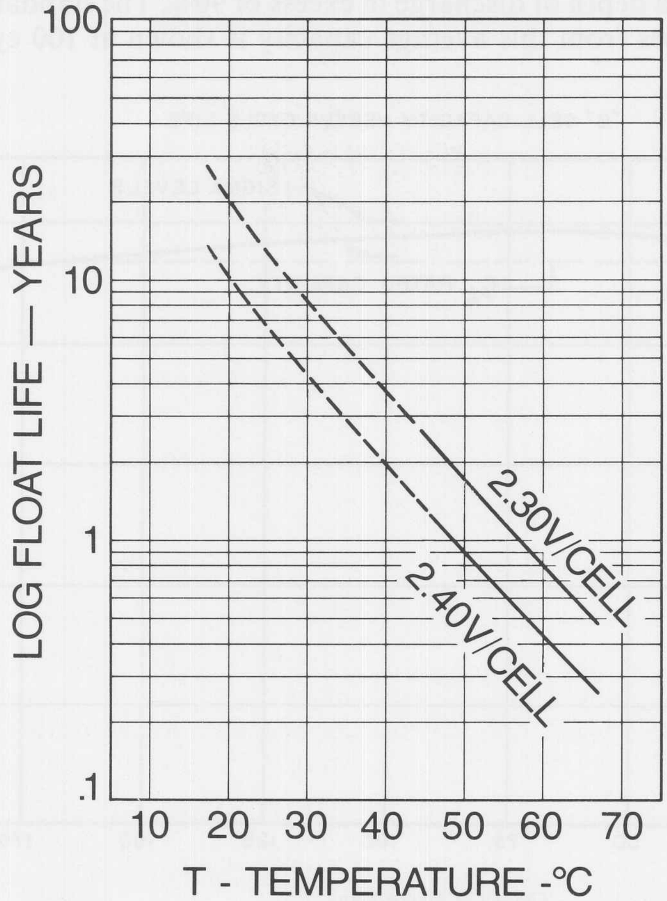


Figure 4

The results of the test data in Table 1 demonstrate the recombination of the Gates cell. These cells were cycled between successive overcharge periods; all tests were with five amp hour "X" cells. If the cells were vented, overcharge should result in the loss of 0.3 gms/amp hour because of the electrolysis of water; therefore, the cells should have lost:

550 amp hours X 0.3 gm/amp hour = 165 gms;

hence the recombination efficiency was:

$$\frac{165 \text{ gms} - 0.7 \text{ gms lost} \times 100}{165 \text{ gms calculated loss}} = 99.6\%$$

These data also show that the cell capacities changed by only 10% during this test at overcharge rates up to the C/4 rate.

TABLE 1

Successive Overcharge Periods (Discharges Between)
3 cells
- **16 days 200 MA**
- **16 days 200 MA**
- **7 days 500 MA**
- **7 days 800 MA**
- **7 days 1.2A 550 A-H Total Overcharge**

Co. - 4.7A-H @ 1A Discharge
Cf - 4.3A-H @ 1A Discharge
Weight Loss - 0.7g

The float life and minimal water-loss characteristics provide a truly maintenance-free battery with long, reliable life.

SECTION 10

SAFETY PRECAUTIONS

There are two primary considerations relative to the application of Gates cells and batteries that should be recognized in order to assure that the usage is safe and proper. These are:

1. GASSING
2. SHORTING

1. Gassing

Lead-acid batteries produce hydrogen and oxygen gases internally during charging and overcharging. These gases are released in an explosive mixture from *conventional* lead-acid batteries, and therefore must not be allowed to accumulate in a gas-tight container. An explosion could occur if a spark were introduced.

The Gates battery is unique in lead-acid battery technology in that there is 100% recombination of the oxygen gas produced at recommended rates of charging and overcharging and therefore no oxygen outgassing. During normal operation, there is some hydrogen gas and also some carbon dioxide gas given off. The hydrogen outgassing is essential with each cycle to insure continued internal chemical balance. The pure lead grid construction of the Gates battery minimizes the amount of hydrogen gas produced. Carbon dioxide is produced by oxidation of organic compounds in the cell.

The minute quantities of gases which are released from the Gates cell with recommended rates of charge and overcharge will normally dissipate rapidly into the atmosphere. Hydrogen gas is difficult to contain in anything but a metal or glass enclosure; i.e., it can permeate a plastic container at a relatively rapid rate. Because of the characteristics of gases and the relative difficulty in containing them, most applications will allow for their release into the atmosphere. However, if the Gates battery is being designed into a gas-tight container, precautions must be taken so that the gases produced can be released to the atmosphere. If hydrogen is allowed to accumulate and mix with the atmosphere at a concentration of between 4% and 79% (by volume at STP), an explosive mixture would be present which would be ignited in the presence of a spark or flame.

Another consideration is the potential failure of the charger. If the charger malfunctions causing higher-than-recommended charge rates, substantial volumes of hydrogen and oxygen will be vented from the cell. This mixture is explosive and should not be allowed to accumulate. Adequate ventilation is required. Therefore, despite its significant advantages over other lead-acid batteries, THE GATES BATTERY SHOULD NEVER BE OPERATED IN A GAS-TIGHT CONTAINER.

The cells should never be totally encased in a potting compound since this prevents the proper operation of the venting mechanism and free release of gas.

Furthermore, considerable pressure can build up in a gas-tight container. This can occur during storage because of the continuous generation of carbon dioxide gas. This pressure is further compounded during charging by the generation of hydrogen.

2. Shorting

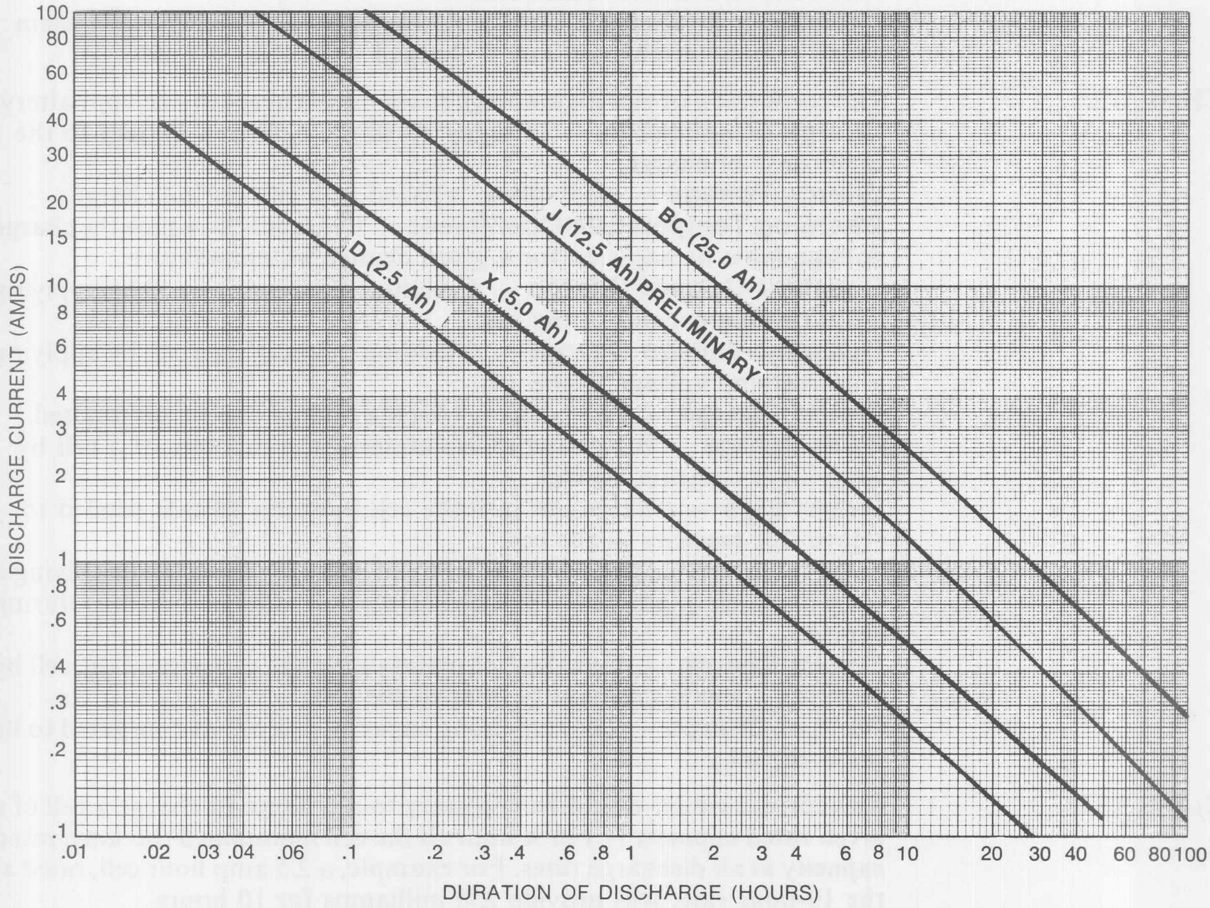
The cells have low internal impedance and thus are capable of delivering high currents if externally shorted. The resultant heat can cause severe burns and is a potential fire hazard. Particular caution should be used when the person working near the open terminals of cells or batteries is wearing metal rings or watchbands. Inadvertently placing these metal articles across the terminals could result in severe skin burns.

Care should also be exercised while shipping cells and batteries when the terminals are not covered in a plastic case. The cells should be packed tightly, preferably with separations between each cell, so that they cannot fall over and short out against each other. These batteries are extremely heavy and require substantial packaging materials in order to keep the package intact during shipment. If there is any doubt as to the safety of the product during shipment, the open tabs should be covered with an insulating material. The packaging which Gates uses has undergone substantial testing and is proven to be a safe container for the shipment of these goods. We would recommend its reuse whenever possible when you are shipping these products.

SECTION 11

SPECIFICATIONS

The "X" and "D" cell capacities as shown in this graph are a representation of data collected by the Gates Energy Products' laboratory from sampled standard production; 90% of all cells produced by Gates Energy Products meet or exceed these discharge capacities. New cells must be cycled or floated appropriately before full rated capacity as shown on these curves is reached. These discharge times represent the capacity available to the knee of the discharge curve.



Glossary

AMP HOURS: The current in amperes multiplied by the time in hours the current is drawn. Capacity is expressed in amp hours.

BATTERY: Two or more cells connected together.

CAPACITY: The ampere hours available from a cell or battery.
Discharge Capacity — The ampere hours which may be obtained from a fully-charged cell or battery during discharge.
Rated Capacity (C) — The discharge capacity in ampere hours which the manufacturer specifies may be obtained from a cell or battery at a given discharge rate.

CELL: An electrochemical system which converts chemical energy into electrical energy and also the reverse for rechargeable units.
Cell Reversal — The act of driving a cell into reverse polarity by excessive discharge.
Primary Cell — An electrochemical device which is discharged only once and is then discarded.
Secondary or Storage Cell — A reversible electrochemical system which may be discharged and recharged a number of times.

CHARGE: The conversion of electrical energy to chemical energy in a cell or battery.
Charge Equalization — Bringing all of the cells in a battery to the same state of charge.
Charge Voltage — The voltage applied to a cell during charge.
Charging Temperature Coefficient — The factor by which the charge voltage must be adjusted for a given change in temperature.
Constant-Current Charge — A method of charging a cell by applying a nonvarying current to the cell.
Constant-Voltage Charge — A method of charging a cell by applying a nonvarying voltage to the cell.
End of Charge — The point at which a charge can be terminated.
Float Charge — A method of maintaining the capacity of a cell by applying a constant voltage.
Overcharge — Charge put into the cell in excess of that needed to return full capacity to the cell.
Taper Current Charge — A method of charging the cell by applying a current which is gradually reduced as the cell voltage increases during charge.
Trickle Charge — A method of maintaining the capacity of the cell by applying a small, constant current to the cell.
State of Charge — The remaining capacity of a cell as compared to its rated capacity.

C/X RATE: The current which would be necessary to discharge or charge a cell of a given rated capacity (C) in X hours if the cell maintained the same rated capacity at all discharge rates. For example, a 2.5 amp hour cell, rated at the 10-hour rate, will provide 250 milliamps for 10 hours.

CYCLE: A charge plus a discharge.
Cycle Life — The number of cycles obtainable from a cell under given conditions.

CONCENTRATION POLARIZATION: The effect of nonequilibrium concentrations of electroactive materials on the cell voltage.

DISCHARGE:	The conversion of chemical energy to electrical energy in a cell or battery. **Depth of Discharge** — The percent of rated capacity removed from a cell during a discharge. **Discharge Rate** — See C/X rate. (C = rated capacity; X = hours of discharge). **Pulse Discharge** — A noncontinuous discharge. **Self-Discharge** — Conversion of the active materials in a cell from the charged to the discharged state on open circuit. **Self-Discharge Rate** — The percent of capacity lost in a cell on open circuit over a specified period of time.
ELECTRODE:	A conducting mass containing materials which are capable of reacting with the electrolyte to produce or accept current.
ELECTROLYSIS:	The electrochemical decomposition of water from the electrolyte.
GRID:	The current collector portion of the electrode.
INTERNAL RESISTANCE OR IMPEDANCE:	The apparent change in voltage as a function of current caused by resistive and polarization effects.
MAINTENANCE-FREE:	A term used for a type of cell which may be operated without adding water to the electrolyte during its recommended life.
OUTGASSING:	The release of gas from a cell during operation.
OXYGEN CYCLE:	The mechanism whereby the oxygen which is evolved at the positive plate during overcharge diffuses to and reacts with the negative plate in a continuous manner.
PLATE:	An electrode.
RECOMBINATION:	The mechanism whereby oxygen reacts with the negative plate to prevent loss of water from the system.
SEPARATOR:	The material used to isolate the positive and the negative electrodes from each other.
THERMAL RUNAWAY:	A condition in which a cell or battery on constant-potential charge can destroy itself through internal heat generation.
UTILIZATION:	The percent of rated capacity which can be obtained from a cell or battery during discharge under specified conditions.
VOLTAGE:	**Float Voltage** — A constant voltage applied to a cell or battery to maintain its capacity. **Nominal Voltage** — The average voltage of a source. **Open-Circuit Voltage** — The no-load voltage of a cell. **Over-Voltage** — The difference between the measured and the equilibrium voltage of a cell. **Voltage Regulation** — The relative percent change of voltage during discharge.
WATT HOURS:	The capacity of a cell multiplied by its nominal voltage. The energy of a cell is expressed in watt hours.

GATES SEALED RECHARGEABLE BATTERIES

standard cells and batteries

Cells

Product Number	Voltage	Capacity (Ampere-Hours) 20 Hr. Rate	10 Hr. Rate	Discharge Current at 10 Hr. Rate	Height (Incl. Terminals) in/mm	Diameter in/mm	Weight (Approx.) lb/kg	Package
0810-0004	2	2.7	2.5	250mA	2.65/67	1.34/34	.40/.18	D Cell
0800-0004	2	5.2	5.0	500mA	3.17/81	1.74/44	.81/.37	X Cell
0840-0004*	2	13.0	12.5	1250mA	5.34/136	2.04/52	1.85/.84	J Cell
0820-0004	2	26.0	25.0	2500mA	6.78/172	2.55/65	3.49/1.58	BC Cell

*J Cell information is preliminary. Contact Gates Energy Products, Inc., for up-to-date information.

Batteries

Product Number	Voltage	Capacity (Ampere-Hours) 20 Hr. Rate	10 Hr. Rate	Discharge Current at 10 Hr. Rate	Length in/mm	Width in/mm	Height** in/mm	Weight (Approx.) lb/kg	Package
0810-0011	6	2.7	2.5	250mA	4.20/107	1.53/39	2.69/68	1.32/.60	1x3D-Case
0810-0102	6	2.7	2.5	250mA	4.00/102	1.48/38	2.63/67	1.23/.56	1x3D-Shrink
0810-0017	6	2.7	2.5	250mA	2.63/67	2.63/67	3.84/98	1.53/.69	Cluster D-Lantern
0800-0011	6	5.2	5.0	500mA	5.42/138	1.94/49	3.10/79	2.58/1.17	1x3X-Case
0800-0102	6	5.2	5.0	500mA	5.22/133	1.86/47	3.08/78	2.43/1.11	1x3X-Shrink
0802-0008	6	10.4	10.0	1000mA	5.38/137	3.64/92	3.14/80	5.23/2.37	2x3X-Case
0802-0016	6	10.4	10.0	1000mA	5.20/132	3.60/91	3.08/78	4.86/2.20	2x3X-Shrink
0820-0014	6	26.0	25.0	2500mA	8.05/204	2.85/72	7.16/182	11.08/5.02	1x3BC-Case
0822-0008	6	52.0	50.0	5000mA	8.05/204	5.45/138	7.16/182	22.30/10.12	2x3BC-Case
0800-0027	8	5.2	5.0	500mA	7.16/182	1.94/49	3.10/79	3.43/1.56	1x4X-Case
0800-0104	8	5.2	5.0	500mA	6.96/177	1.86/47	3.08/78	3.33/1.51	1x4X-Shrink
0810-0008	12	2.7	2.5	250mA	4.20/107	2.87/73	2.69/68	2.61/1.18	2x3D-Case
0810-0016	12	2.7	2.5	250mA	8.22/209	1.53/39	2.69/68	2.61/1.18	1x6D-Case
0810-0108	12	2.7	2.5	250mA	8.01/203	1.48/38	2.63/67	2.48/1.13	1x6D-Shrink
0810-0114	12	2.7	2.5	250mA	4.00/102	2.82/72	2.63/67	2.44/1.11	2x3D-Shrink
0800-0008	12	5.2	5.0	500mA	5.42/138	3.68/93	3.10/79	5.18/2.35	2x3X-Case
0800-0016	12	5.2	5.0	500mA	10.63/270	1.94/49	3.10/79	5.26/2.39	1x6X-Case
0800-0108	12	5.2	5.0	500mA	10.41/264	1.83/46	3.08/78	4.93/2.24	1x6X-Shrink
0800-0114	12	5.2	5.0	500mA	5.22/133	3.60/91	3.08/78	4.85/2.20	2x3X-Shrink
0820-0020	12	26.0	25.0	2500mA	8.05/204	5.45/138	7.16/182	22.30/10.12	2x3BC-Case

**Height given excludes battery tabs. For height including tabs, please add the following:

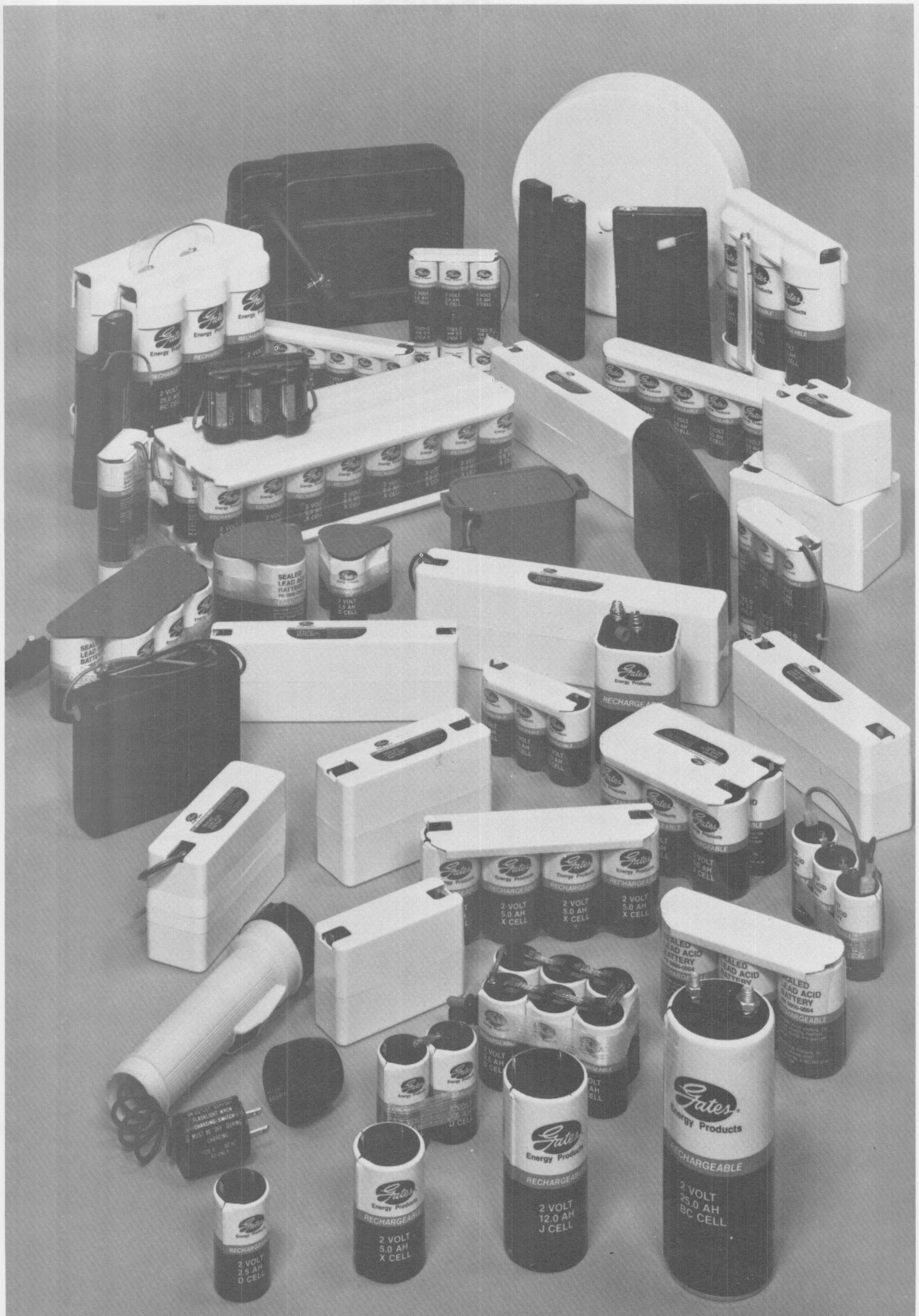
	D in/mm	X in/mm
Case	.02/1	.12/3
Shrink	.08/2	.14/4

Note: Standard lead wires for the above available at extra cost are:

0810: 18 AWG Plain Ends, Red Positive, Black Negative, Extended 9.0 + ½ in. outside cell pack.

0800: 16 AWG Plain Ends, Red Positive, Black Negative, Extended 9.0 + ½ in. outside cell pack.

Special lead assemblies and/or battery configurations are available upon request.


Gates
Energy Products
RECHARGEABLE
2 VOLT
25.0 AH
BC CELL
2 VOLT
12.0 AH
J CELL
2 VOLT
5.0 AH
X CELL
2 VOLT
2.5 AH
D CELL
SEALED
LEAD ACID
BATTERY

Notes